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AFFDL-TR-71-62 VOLUME IX

DESIGN STUDIES AND MODEL TESTS OF THE STOWED TILT ROTOR CONCEPT

Volume IX. Value Engineering Report

Jaan Liiva
H. J. Rose
The Boeing Company, Vertol Division

TECHNICAL REPORT AFFDL-TR-71-62

OCTOBER 1971

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AERONAUTICAL SYSTEMS DIVISION
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66

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) The Boeing Company, Vertol Division Boeing Center, P.O. Box 16858 Philadelphia, Pa. 19142	2a REPORT SECURITY CLASSIFICATION Unclassified 2b GROUP	
3 REPORT TITLE DESIGN STUDIES AND MODEL TESTS OF THE STOWED TILT ROTOR CONCEPT (Volume IX. Value Engineering Report)		
4 DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report, July 1 to August 31, 1970 and June 1 to July 25, 1971		
5 AUTHOR(S) (Last name, first name, initial) Jaan Liiva H. J. Rose		
6 REPORT DATE October 1971	7a TOTAL NO OF PAGES 59	7b NO OF REFS 3
8a CONTRACT OR GRANT NO F33615-69-C-1577 b. PROJECT NO. c d	9a ORIGINATOR'S REPORT NUMBER(S) D213-10000-9 9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFFDL-TR-71-62, Volume IX	
10 AVAILABILITY/LIMITATION NOTICES Approved for Public Release - Distribution Unlimited		
11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY Air Force Flight Dynamics Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio	

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DD FORM 1 JAN 64 1473

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NOTICE

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Stowed Rotor Tilt Rotor Rotor Feathering Rotor Folding Hingeless Rotor Value Engineering						

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DESIGN STUDIES AND MODEL TESTS OF THE STOWED TILT ROTOR CONCEPT

Volume IX. Value Engineering Report

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FOREWORD

This value engineering report was prepared by The Boeing Company, Vertol Division, Philadelphia, Pennsylvania, for the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, under Phase II of Contract F33615-69-C-1577. The contract objective is to develop design criteria and aerodynamic prediction techniques for the folding tilt rotor concept through a program of design studies, model testing and analysis. This report covers the time periods from July 1 to August 31, 1970 and June 1 to July 25, 1971.

The contract was administered by the Air Force Flight Dynamics Laboratory with Mr. Daniel E. Fraga (FV) as Project Engineer.

Acknowledgement is made to the following contributors to this report: J. Wisniewski, D. Board, F. Sauter and N. Weir.

The other reports published under this contract for Design Studies and Model Tests of the Stowed Tilt Rotor Concept are:

Volume I	Parametric Design Studies
Volume II	Component Design Studies
Volume III	Performance Data for Parametric Study Aircraft
Volume IV	Wind Tunnel Test of the Conversion Process of a Folding Tilt Rotor Aircraft Using a Semi-Span Unpowered Model
Volume V	Wind Tunnel Test of a Powered Tilt Rotor Performance Model
Volume VI	Wind Tunnel Test of a Powered Tilt Rotor Dynamic Model on a Simulated Free Flight Suspension System
Volume VII	Wind Tunnel Test of the Dynamics and Aerodynamics of Rotor Spinup, Stopping and Folding on a Semi-Span Folding Tilt Rotor Model
Volume VIII	Summary of Structural Design Criteria and Aerodynamic Prediction Techniques
Volume IX	Value Engineering Report

This report has been reviewed and is approved.

Ernest J. Cross, Jr.
Lt. Colonel, USAF
Chief, Prototype Division

ABSTRACT

This report describes and compares the technical and cost issue of flush and edgewise folding of the rotor blades for a Stowed Tilt Rotor Aircraft. Four different folding actuation schemes are presented. A cost saving recommendation is also made for the hub casting.

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LIST OF SYMBOLS

R	NUMBER OF FAILURES PER FLIGHT HOUR
T	OPERATING MISSION TIME IN HOURS
α_F	FUSELAGE ANGLE OF ATTACK IN DEGREES
δ_F	FLAP ANGLE IN DEGREES
$\partial C_M/\partial C_L$	AIRCRAFT PITCHING MOMENT DERIVATIVE WITH RESPECT TO AIRCRAFT LIFT
ΔC_D	INCREMENTAL AIRCRAFT DRAG COEFFICIENT BASED ON WING AREA
λ	FAILURE RATE, FAILURES PER FLIGHT HOUR

1.0 INTRODUCTION

The Value Engineering program described in this report compares the relative merits of two different methods of folding the rotor blades on the Stoppable Rotor Concept:

1. Baseline Flush Folding Method (Figure 1)
2. Edgewise Folding Method (Figure 2)

Four different methods of folding actuation are compared:

Scheme #1. (Baseline) Hydraulic Rotary Vane Actuator mounted internally in the hub.

Scheme #2. Ball Screw Fold Actuators driving each blade individually.

Scheme #3. Linear Hydraulic Actuator driving a collector ring to synchronize blade fold.

Scheme #4. Same as No. 2 but the electric actuators are replaced by the failsafe hydraulic actuators.

The failsafe ball screw actuator used in folding method 4 was designed under USAF Contract F33615-69-C-1570 for application as the nacelle tilting actuator for a tilt rotor aircraft and a patent application has been filed.

The two methods for blade folding and the four schemes for actuation are compared from a technical point of view as well as product assurance considerations. Aircraft performance, weight, blade folding loads, blade dynamic stability and aircraft stability and control, maintainability and reliability are discussed

In addition, the cost savings from an alternate clamshell concept for manufacturing the hub is presented.

A total of 836 manhours were spent in the performance of the work covered in this report.

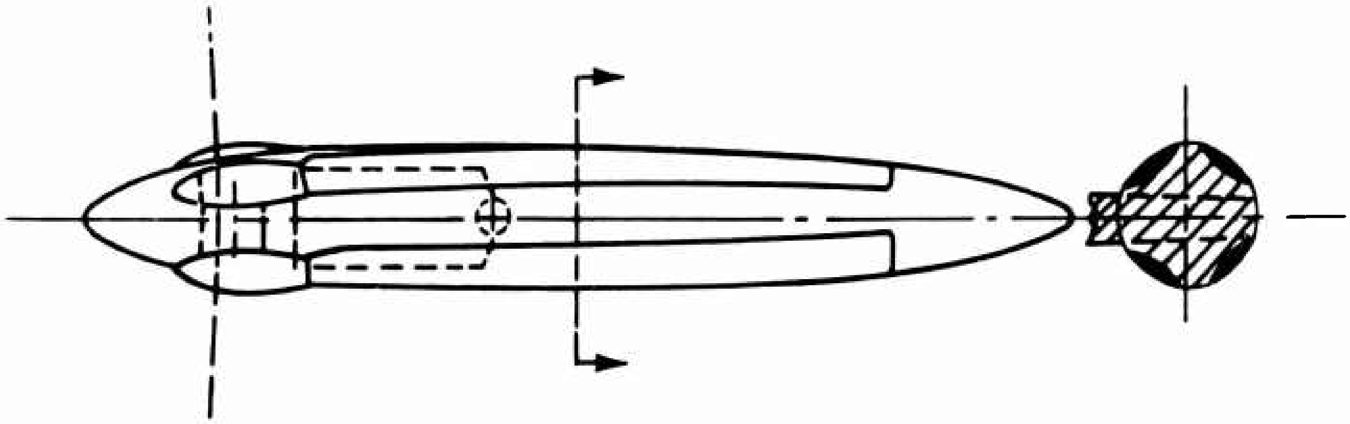


Figure 1. Baseline Flush Folding Method

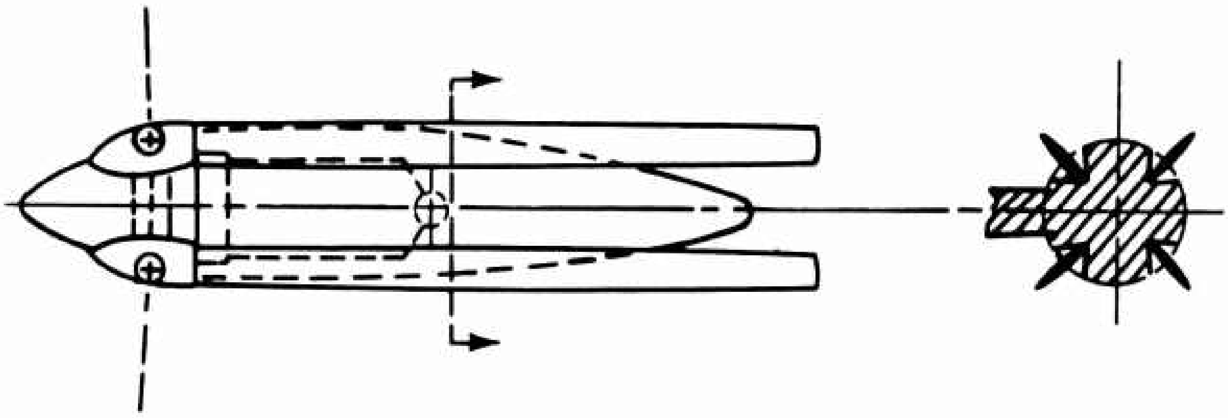


Figure 2. Edgewise Folding Method

2.0 SUMMARY AND RECOMMENDATIONS

A value engineering study was conducted to accomplish the following objectives:

a) Compare flatwise and edgewise folding from technical and product assurance points of view.

b) Identify weak points in the baseline design and evaluate alternate schemes.

c) Recommend a design for further development.

Four alternate schemes were evaluated for each folding method. A study was also performed on an alternate hub design to reduce manufacturing cost.

Flatwise folding was found to be superior to edgewise folding for the following reasons:

a) A 25% increase in airplane drag was measured for the edgewise method from the greater exposure of the blade, and from the slots between blade and nacelle, (Section 4.1). This can be reduced somewhat by providing seals between the nacelle and the nesting blade.

b) An estimated 280-pound increase in weight empty (0.63% W.E.) results from the structural changes and seals required to provide edgewise folding, (Section 4.2). Further increases in weight will result from increased fuel for the mission and growth of the aircraft required to perform the mission due to the increased drag and weight.

c) Blade loads are slightly lower for flatwise folding but are not critical for either method, (Section 4.4).

d) The maintainability of the nacelle wells for edgewise folding requires heating and drainage and frequent cleaning to prevent foreign matter and ice formation, (Section 5.1).

e) The nacelle for flatwise folding is simpler and cheaper to manufacture. There is a negligible increase in complexity and cost from the flatwise fold blade angle control schedule requirements, (Section 5.3).

Scheme 4 with the failsafe ball screw actuator is shown to be superior for the following reasons:

a) Maintainability of the system is easy. It is completely accessible with no in the way components.

b) The safety reliability of the failsafe jackscrew actuator is several orders of magnitude better than Schemes 1, 2 and 3.

c) The overall weight of Scheme 4 is estimated to be 118 pounds lighter than Scheme 1.

d) The cost of Scheme 4 is higher than Scheme 2. This cost can be reduced to be comparable to Scheme 2 by redesigning the system to use a single actuator and linkage arrangement.

The clamshell hub concept developed by value engineering design is 27% cheaper for a steel hub and 22.3% cheaper for a titanium hub than the baseline one piece hub.

Recommendations

A detailed design of the folding mechanism required for the flatwise folding using the failsafe fold actuator (Scheme 4) should be performed.

A design should be initiated to utilize one failsafe actuator on the front of each hub and a linkage arrangement to fold all blades simultaneously.

A failsafe actuator should be designed, built and tested.

3.0 DESCRIPTION OF ALTERNATE DESIGN CONCEPTS

In this section of the value engineering report the baseline flatwise folding method with the vane type blade fold actuator mechanism shown in Reference 1 will be briefly described. The weak points in the design are discussed and the alternate schemes are presented.

3.1 BASELINE DESIGN FOR FLATWISE FOLDING (SCHEME 1)

a) General

The rotor system uses hingeless or rigid type rotor blades in which the hub has provision for blade folding, cyclic and collective pitch change, and feathering preparatory to folding. There are no mechanical hinges for flapping or lag-rotor-blade motion.

b) Description of Folding Tilt Rotor Hub and Fold Mechanism

Figure 3 shows the basic features currently envisioned as necessary in the folding-tilt-rotor hub mechanism. The basic four bladed propeller hub mechanism consists of a central octagonal box structure with a family of lugs arranged in a pattern of four sets around each blade station. These lug sets fit exactly with mating lug sets in each pitch change bearing housing.

The aft two sets of lugs, at any discrete blade station, are constantly in mesh with the matching lug sets in the pitch housing via the blade fold hinge pins. The other set of lugs in each respective member is provided to selectively lock the blade pitch change bearing housing in rotor flight, or to release the blade housing during the fold cycle. A set of two hydraulically-locked pins for each blade are engaged to provide positive blade retention. The blade folding motion (approximately 90°) and synchronization is accomplished by the outer folding link, and the hydraulic rotary vane folding actuator. The blade folding motion is accompanied by pitch change motion as shown in Figure 4 which rotates the blade to a flat position during the last portion of the foldback angular motion. This pitch change with fold motion is provided by a piston and roller assembly riding in parallel, keyway-type slots with helical cam slot endings connected to the outer fold links.

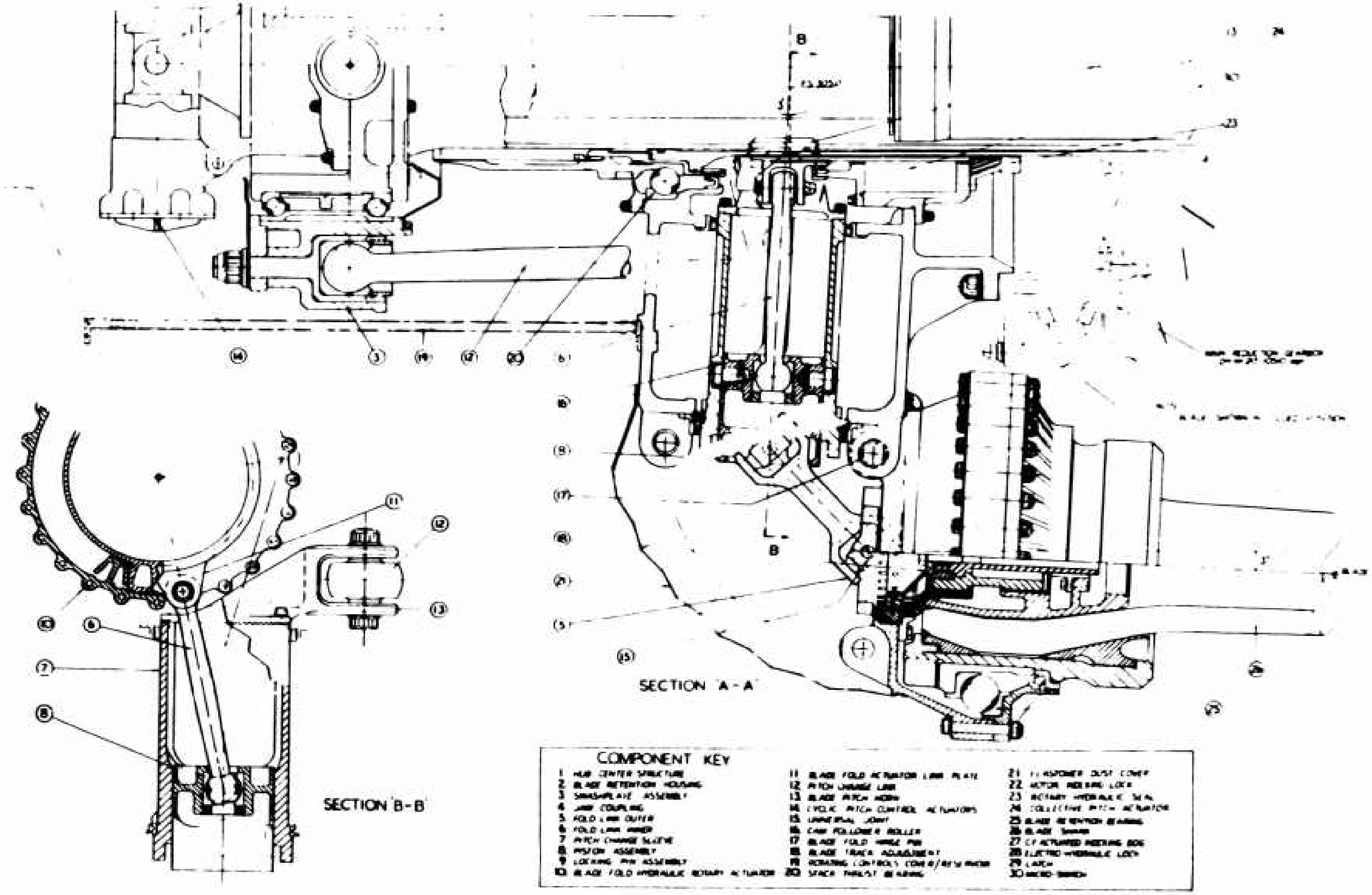


Figure 3. Rotor Hub and Blade Folding Assembly (Sheet 1 of 2).

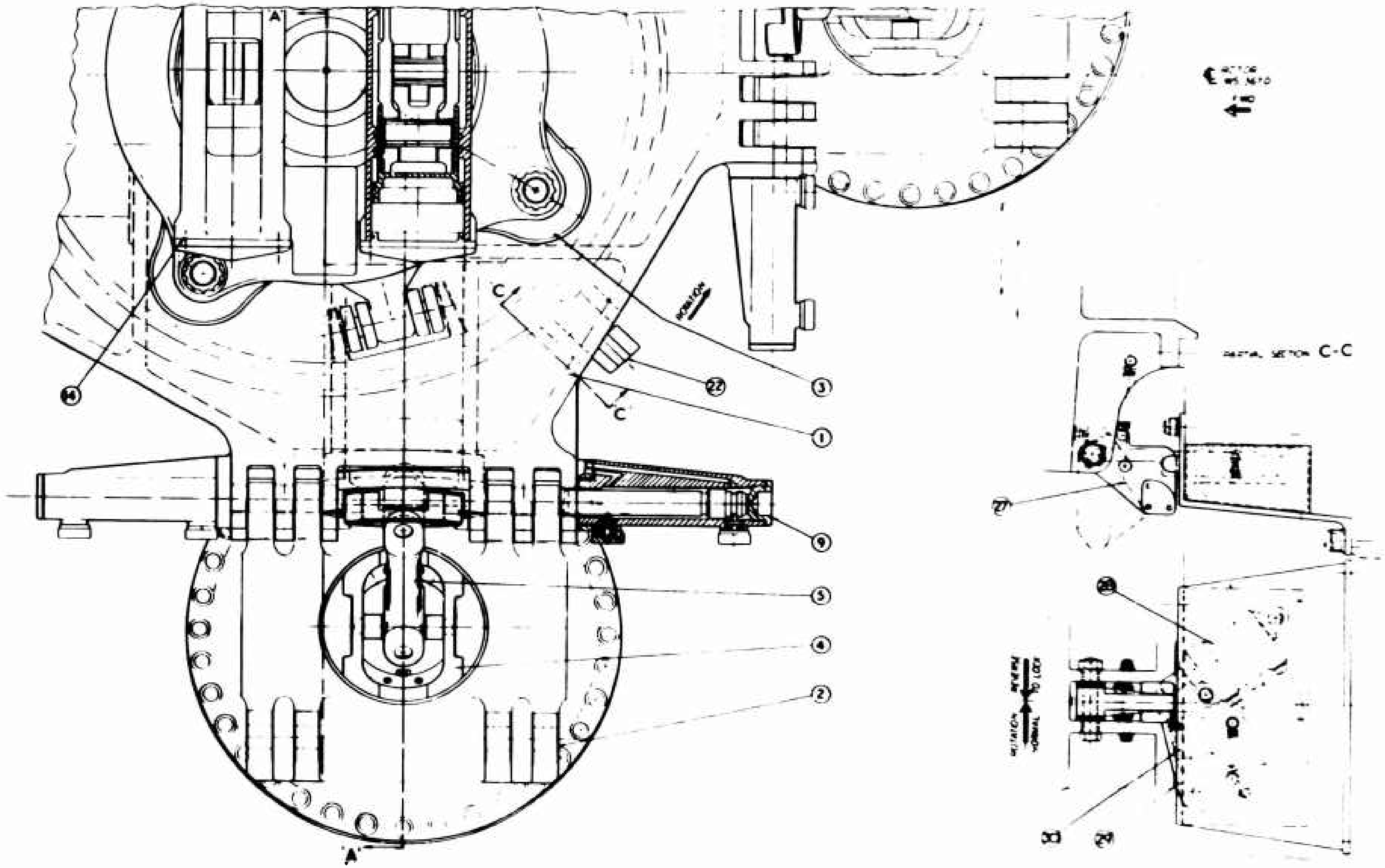


Figure 3. Rotor Hub and Blade Folding Assembly (Sheet 2 of 2).

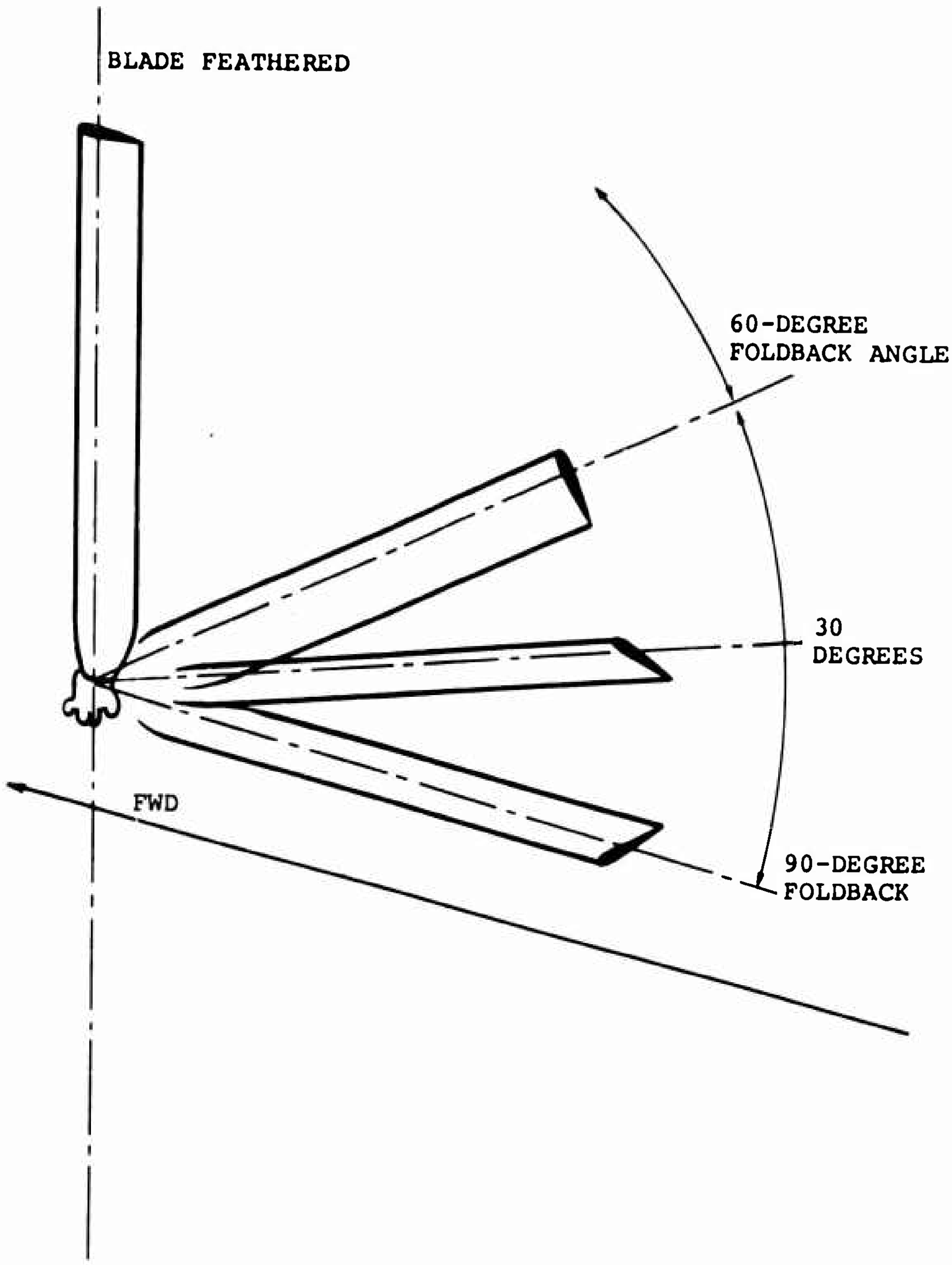


Figure 4. Rotor Blade Fold Sequence.

Thus, at the initiation of blade folding, the blade is in a feathered position. The parallel keyway type slots accommodate the constant feather angle with fold needed, until, at the last instant of travel, the blade is rotated by the helical cam slots.

The outer fold link provides the torsional connection between the piston and the blade retention. When the blade is deployed (rotor flight position), the outer fold link is pulled into the keyway-grooved cylinder by the piston. A pair of interlocking jaw faces are brought into mesh, thus providing a solid high-torsional-rigidity connection between the pitch change sleeve and the blade. The hub retention area is, therefore, prepared for fully effective rotor flight control.

c. Pitch Change Mechanism

Pitch change is accomplished through a dual-hydraulically-powered helicopter-type control swashplate which transmits blade pitch change, through pitch links, to the blade pitch change sleeve. Different pitch link motion requirements at the end attachment to the swashplate and pitch arm have dictated the use of a pitch link with an integral spherical end bearing at the swashplate end and a conventional rod end bearing at the pitch arm end.

The swashplate assembly is gimbal-supported on a translating tube to allow for collective pitch and feathering pitch change. This sliding tube forms the primary structural component of the actuation package which, in addition to supporting the swashplate, houses dual hydraulic collective actuators and a collective lock unit. A dual pitch actuator system mounted at the forward end of the tube controls swashplate tilt for cyclic pitch change.

The actuation package is contained in the hub and transmission-mounted controls support tube (stack) with actuator forces reacted by the forward support thrust bearing. Control moment forces are reacted by the same bearing and by a steady mount at the aft face of the transmission. The control support thrust bearing transfers the actuator reaction forces into the hub structure so that the aft steady mount transfers only shear and torque reaction forces to the transmission end cover. The swashplate rotating on the ring is driven by the rotating hub through a pair (for balance) of active drive shoes and backup or safety drive shoes. These shoes ride in appropriate drive slots.

d. Lubrication Systems

All bearings are oil lubricated. The complete pitch change mechanism and blade retention systems are totally enclosed by a controls cover, which also serves as a rotating oil sump, and a set of elastomer boots, one at each blade station. While the system is rotating, oil is continually supplied to the bearings from a central oil gallery which is supplied with oil picked up by a non-rotating scoop tube immersed in the rotating oil sump. Oil retention cups are provided at all rolling element bearings so that a "safe" oil supply is maintained for startup and for loss of sump oil through oil seal failure or battle damage.

e. Rotor Indexing Lock

Provision must be made in the rotor system to stop the rotor at either of two discrete locations, so that folding and accurate stowing of the rotor blades may be achieved. In previous studies, a rotor brake and an indexing drive motor were proposed to accomplish this procedure. However, in this report a less complicated method is proposed (see Figure 3). This provision consists of two hinged locking dogs, which, during operation at normal rotor rpm, are forced outward by centrifugal force. These locking dogs spring inward when rpm is reduced, and they depress two spring-loaded latches as they pass over them. A feather blade pitch is selected that will, after stopping the rotor, aerodynamically initiate reverse rotation. The dogs then contact the reverse (upright) faces of the latches and the rotor.

This contact operates a micro-switch within the latch which triggers an electro-hydraulic locking bolt that positively locks the rotor in position. Cross-coupling of the micro-switches and contact sensing of locking dogs would insure against switch failure or rotor bounce.

f. Spinner

An aerodynamic spinner is designed in three sections. The forward or nose section is quickly removable to provide access to rotor system test points. The mid or ogive section covers the general area of the rotating oil sump and may also be built in several radial segments for easy removal and fabrication. The aft or skirted section is contoured to fit around each blade station and carries hinged doors which extend and retract in phase with the blade fold motion thereby providing smooth aerodynamic fairing over the retracted folded blades. All spinner shells are made of fiber glass-honeycomb construction and attach to substructure frames built over the forward hub and controls cover region.

g. Blade Vernier Adjustment - Tracking

Blade pitch vernier adjustment is provided for by using a screw jack operated dual spline concept. The dual spline sleeve consists of a helical spline and a straight spline. The axial motion, imparted to the dual spline sleeve by the screw jack, positions the blade with respect to the jaw clutch plate, and thus, provides a positive blade tracking means. All adjustment is provided with positive lock means to insure continuous safe operation at any setting.

h. Aids

Provisions are made for locating a rotor systems ground test panel and slip rings on the forward face of the controls cover (rotating sump). These items would be a part of a failure detection indication system for the non-rotating components. Provision could be made for ground check-out during general maintenance inspections, or, if desired, an advanced version could be developed to provide cockpit readout. Advanced systems will probably require that this second system be specified as standard equipment in the future. Structural integrity or condition monitors can be used in many of the subsystem areas to enhance in-flight safety, and to insure flying in safe time periods on all components.

i. Safety Features

A zero-degree cyclic pitch lock is incorporated into the cyclic actuator system to insure that there will be no cyclic pitch present on the rotor when the nacelle is in the full down position. This lock is mechanically capable of holding the swashplate stable at zero-degree cyclic in case of loss of hydraulic power to the cyclic actuators in propeller mode. At the aft end of the collective actuators, the infinite position lock, with emergency electrical override for feathering (a manual pitch) change, is provided for additional safety in transition in case of loss of sufficient hydraulic power to the collective-feathering actuator.

3.2 ALTERNATE DESIGNS

The criteria for edgewise folding of the rotor blades is basically the same as for flush folding, except that the blade is not rotated and fits into slits cut into the nacelle as shown in Figure 2. Before any mechanical system is evolved for an edge-fold configuration, a critical analysis of the baseline configuration is in order, to expose any weak points in the design.

Two points come readily to mind, namely:

a) The hydraulic rotary vane actuator requires the disassembly of the hub for maintenance. Also, for some types of failure it not failsafe.

b) The outer fold link has two universal joints, the failure of which would disengage the blade from the folding mechanism.

Therefore a scheme which eliminates reliance on non-redundant mechanisms would be an improvement.

Scheme 1 for Edgewise Folding

This design is exactly the same as the baseline configuration except that the cam follower roller track in the pitch change sleeve is straight instead of curved and the nacelle has slits cut into it to allow the trailing edge of the blade to nest inside the nacelle. Pneumatic seals are provided to seal the blade against the nacelle. Figure 5 shows the nacelle and wing structural arrangement needed to accommodate edgewise folding.

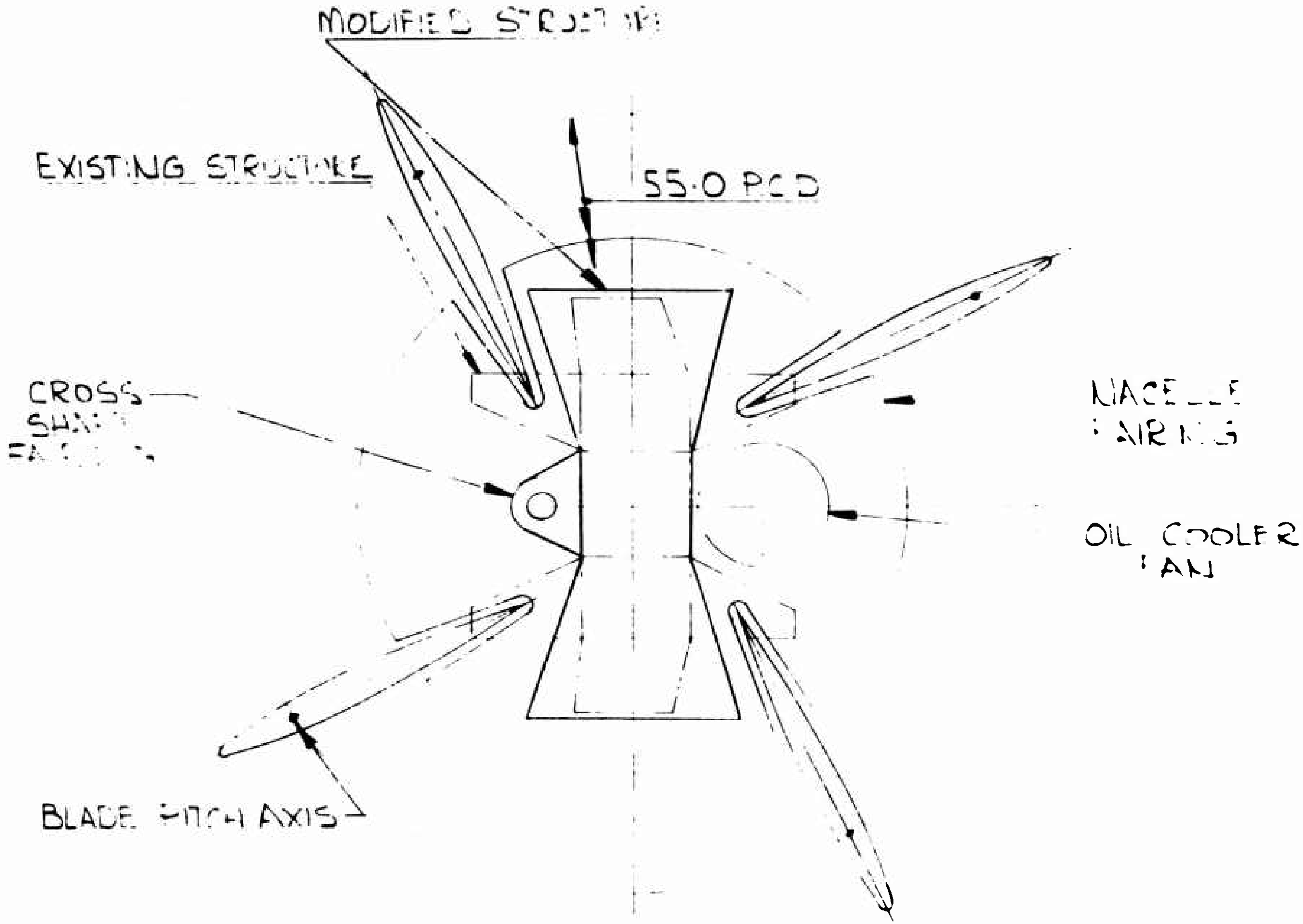


Figure 5. Scheme 1 for Edgewise Folding

Scheme 2 for Flat or Edgewise Folding

This design uses the same mechanism as Scheme 1 for the basic blade fold operation but eliminates the hydraulic rotary vane actuator. In its place a ball screw driven by an electric gear motor provides the motive power for folding as shown in Figure 6. The outer fold link is used in this configuration, only to lock the blade pitch change function.

Scheme 3 for Flat or Edgewise Folding

This scheme, shown in Figure 7, depicts a different configuration of folding actuator. In this design a collector ring slides on the rotor hub housing, powered by four linear hydraulic actuators. These actuators are grounded out into a support ring which also is utilized for pressure and return galleries for the hydraulics. The support ring is fixed to the four blade barrels of the hub. The collector ring has 4 pairs of links which attach to the blade retention housing, one pair per housing. A longitudinal movement of the collector ring folds or deplys the blades. The outer fold link is used in this configuration only to lock the blade pitch change function.

Scheme 4 for Flat or Edgewise Folding

The basic method is the same as Scheme 2 but the electric actuator is replaced with the hydraulic failsafe actuator shown in Figure 8. This is a Boeing device (patent pending) that ensures full stroke in the event of any single failure, e.g., jamming, power failure, etc. It was developed under USAF Contract F33615-69-C-1570 and is described in Reference 3, and some of the advantages are described below.

Non-Jamming Ball Screw Linear Actuator

The actuator shown in Figure 8 consists of a free floating ball screw shaft on either end of which is mounted a ball nut driven through an EPI cyclic gear train by a power unit. The initial drive from the power unit is through a two way "No-Back" which locks the gear system to ground when the power unit is not producing torque. A ball spline synchronizing shaft which also acts as a "No-Back" unlock signal (unlocks the "No-Back" in the event of a power unit failure on that side) drives through a differential gear train. The ball screw shaft is restrained to a linear motion by a keyway cut in the shaft for the full length of the shaft. In the event of a ball nut jamming on the screw, the opposite side continues to function and drives the nut for the full stroke or whatever increment of screw is left when the jam occurs. The ball screw shaft is made up of two concentric rods so that for a break in either, the shaft remains functional. The advantages are as follows:

a) The actuator will provide a full stroke in a jammed condition.

b) The actuator can sustain a power loss without loss of function.

c) The actuator can sustain a break in one concentric shaft without loss of function.

To produce similar reliability in this type of system would require two actuators, jamming of either actuator would cause total loss of functions. Linear actuators have been produced which will give half stroke under jammed condition, but none which will give full stroke.

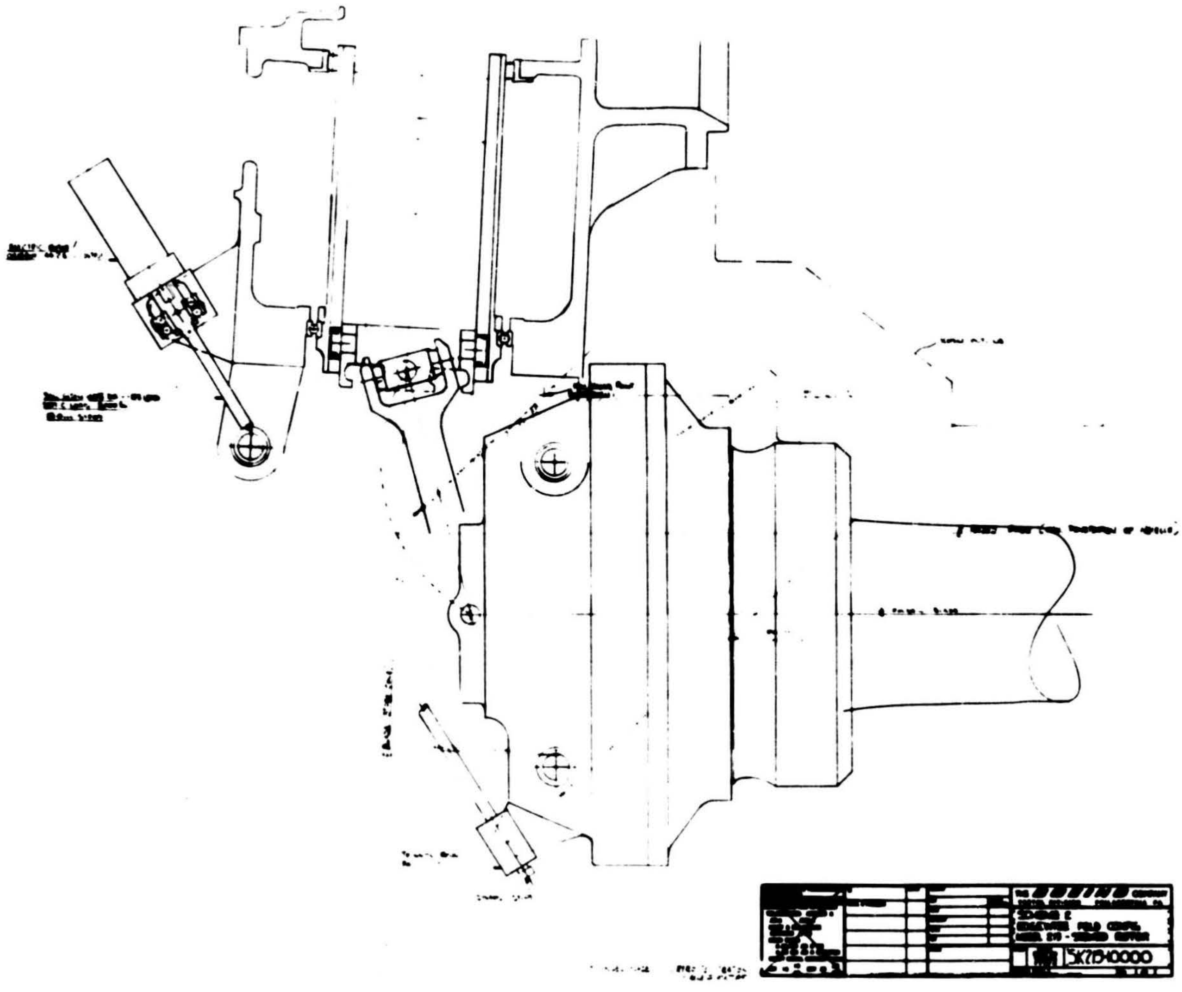


Figure 6. Scheme 2 With Electric Motor Actuation

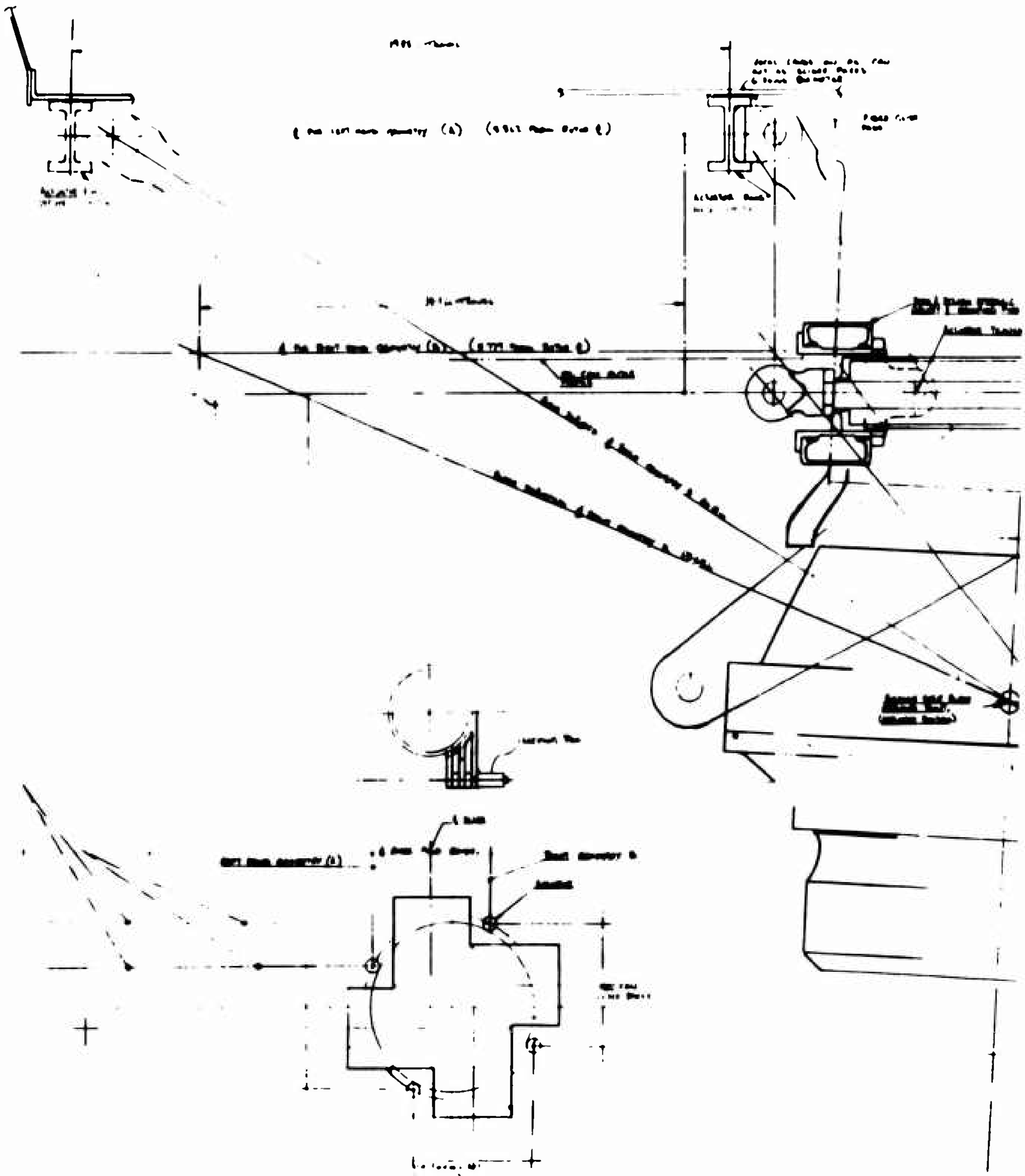
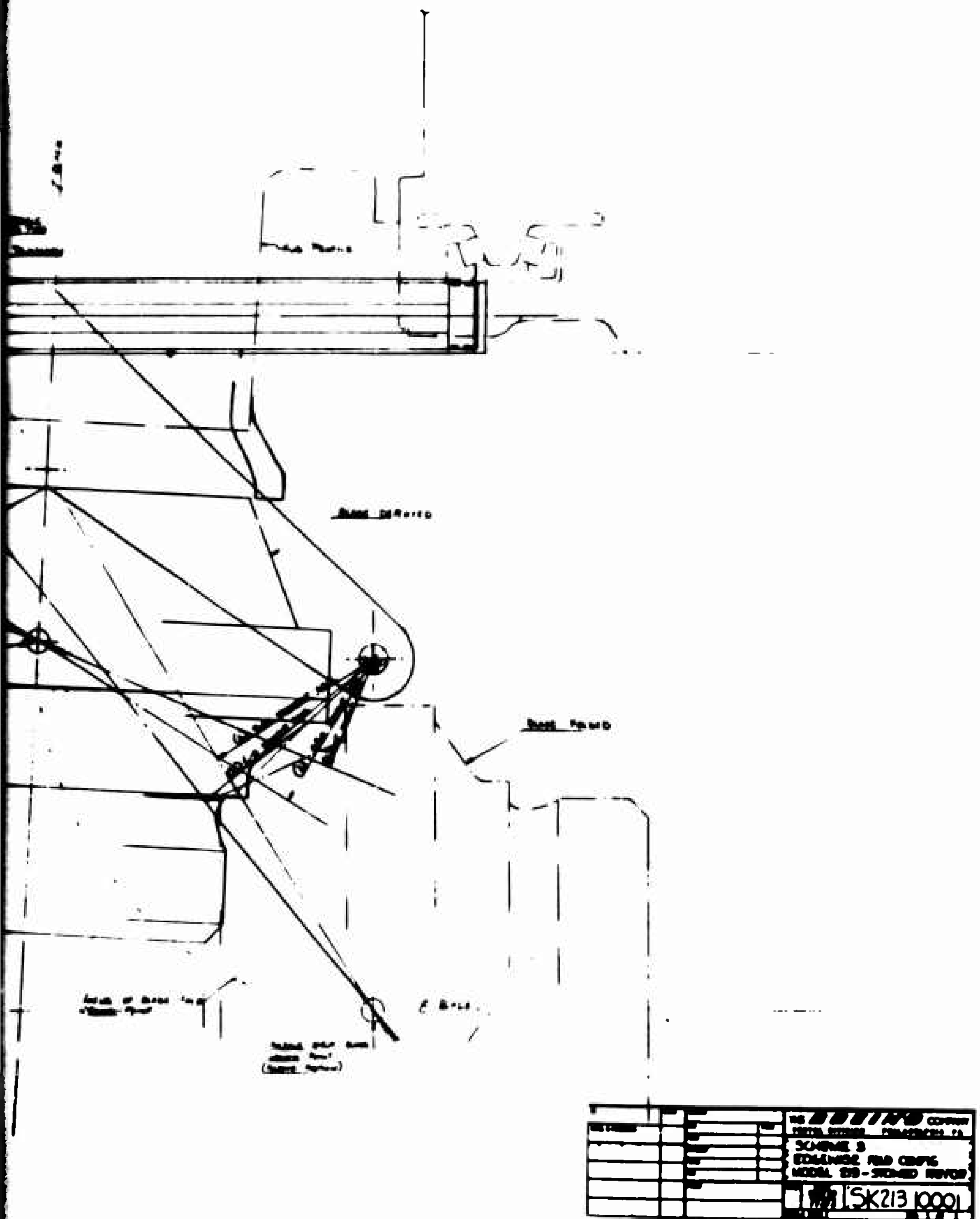


Figure 7. Scheme 3 With Collector Ring Actuation

B



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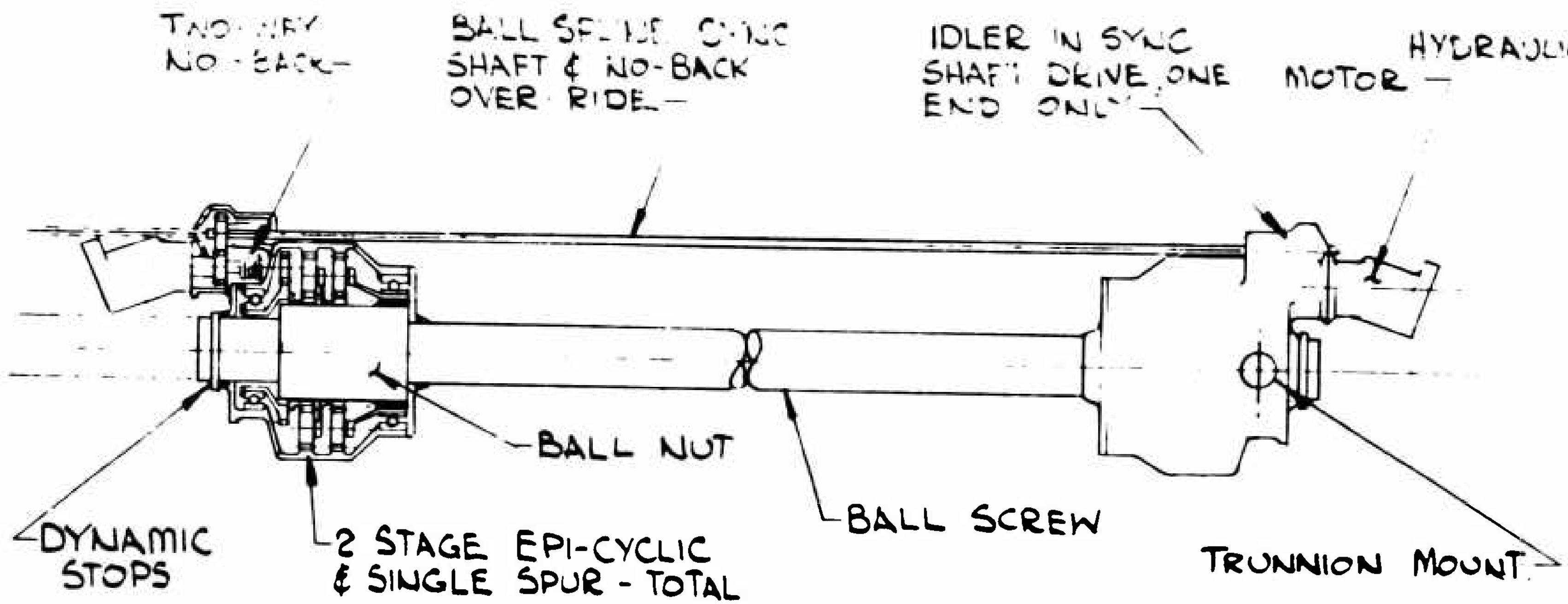


Figure 8. Failsafe Actuator for Blade Folding

4.0 TECHNICAL CONSIDERATIONS

In this section the two different methods of blade folding, flatwise and edgewise, are compared from the standpoint of performance, weight, fold loads, airplane stability and control and blade dynamics. The results from the design studies and wind tunnel tests of Phases 1 and 2 of the contract are summarized here.

4.1 PERFORMANCE

Figure 9 developed from data in Reference 1g, shows that the baseline flatwise folded aircraft has a better payload-radius capability because airplane drag is lower by $\Delta C_D = .0080$ for the flatwise fold aircraft. To achieve comparable performance, the edgewise folded aircraft would need:

1. 2300 pounds more fuel (at max fuel for comparable payload)

2. 67% more horsepower, and be

3. 8000 pounds heavier at takeoff gross weight

4.2 WEIGHTS

A weights summary comparing the delta weights between four different actuation methods for stowing the rotor blades described in Section 3 is presented in Table 4.1. Scheme 1 is the basis for the comparison since it represents the weights included in the original stowed rotor report, Reference 1a. Weights were determined by estimating/calculating from layout drawings and from actual weights of existing aircraft using similar components.

Table 4.1 does not include the weights of items which are common to all the concepts. Weight deltas are shown only for those items which represent differences between the concepts as in the case of the type and number of actuators, mechanical linkages, etc. The weights presented are based on folding the blades flush against the nacelle pod.

The weight penalty associated with folding the blades edgewise against the nacelle pod is an additional 280 pounds per aircraft (140 pounds per rotor assembly). Approximately 80 pounds of this penalty is attributed to the additional structure required to provide the deep cutouts necessary for edgewise folding. The remaining 200 pounds is the estimated weight of the pneumatic tube system and its installation required to lock and seal the folded blades to the nacelle pod. This is described in Section 3.

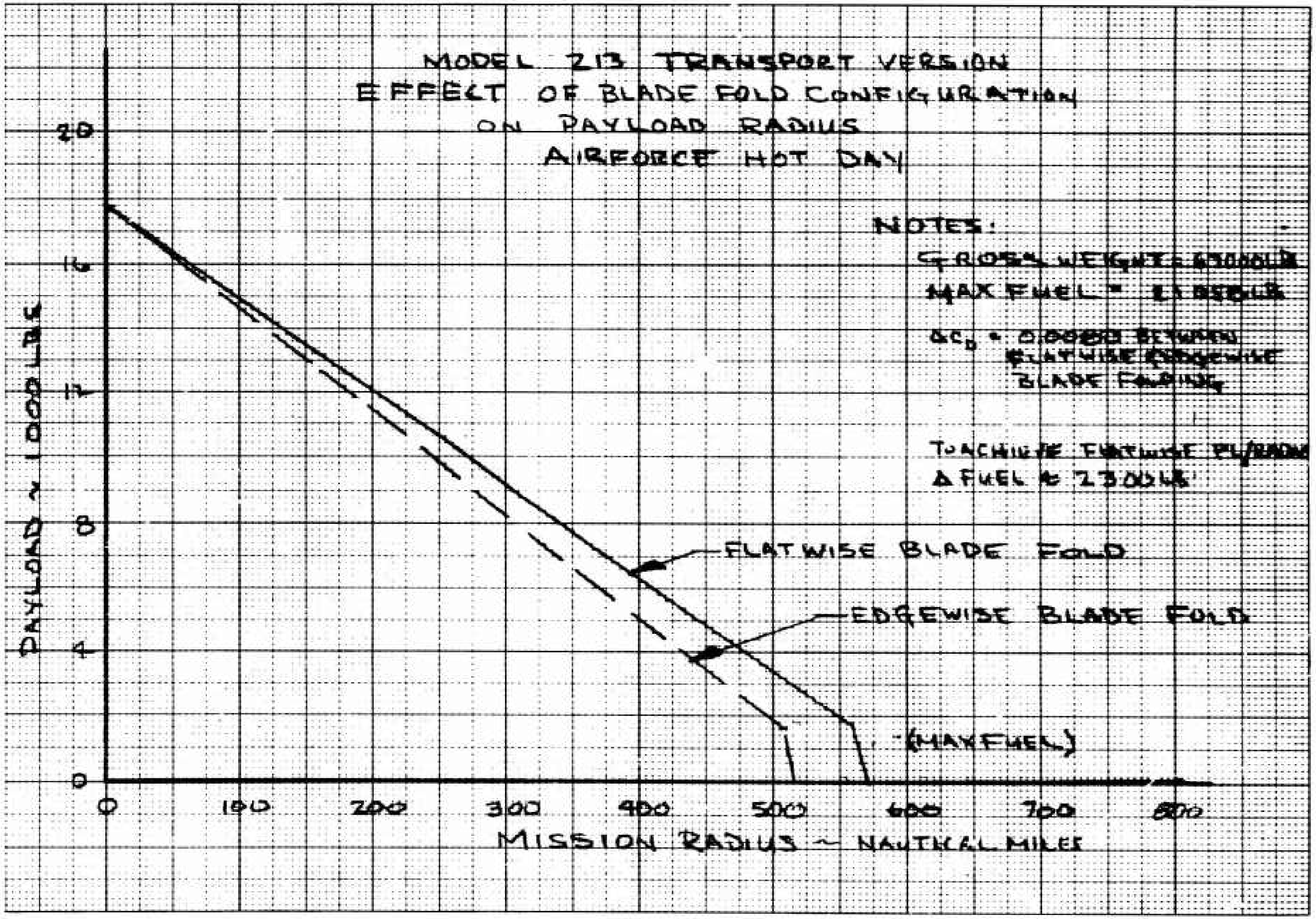


Figure 9. Effect of Nacelle Drag for Edgewise Folding on Payload Radius

TABLE 4.1 WEIGHTS SUMMARY - ALTERNATE DESIGN CONCEPTS

ITEMS	SCHEME NO. 1 BASELINE	SCHEME NO. 2	SCHEME NO. 3	SCHEME NO. 4
ROTARY ACTUATOR	200			
PISTON	48	24	24	24
INNER LINK	32			
STRUT			48	
ELECTRIC ACTUATOR		88		
LUGS - HUB		5		5
LUGS - BLADE ROOT END		5	5	5
HYDRAULIC ACTUATOR			80	
MOUNTING AND ACTUATOR RING ASSY			30	
SLIDE PLATE AND OIL CAN BEEF-UP			36	
NON-JAMMING BALL SCREW LINEAR ACTUATOR				128
WEIGHT PER AIRCRAFT	280	122	223	162

NOTES: 1. WEIGHTS OF COMMON ITEMS TO ALL CONCEPTS ARE EXCLUDED

2. WEIGHTS ARE FOR FLUSH FOLDING ROTOR BLADES

Table 4.2 includes the summary weight statement of the original proposed stowed tilt rotor aircraft, Column (1) and the revised weight statements of the recommended concept with flush folding blades Column (2) and edgewise folding blades, Column (3).

4.3 FOLD LOADS

The results from the folding tests on the 1/9 scale Model 213 (Reference 1g) did not favor one blade folding method over the other from a blade load point of view. The steady loads were slightly less for the flatwise method as shown in Figure 10 but the highest loads in flap bending were only a half of the loads at normal operating RPM, and the highest chordwise loads were only one third. Alternating blade loads were too low to be measured accurately.

4.4 AIRCRAFT STABILITY

The impact of blade folding on stability is to increase the total aircraft stability by removing the unstable rotor contribution. Folding the blades flatwise provided a configuration with lower drag than when folded edgewise but there is no difference between the two configurations in aircraft stability. Data obtained from Test Program IV (Reference 1(g) indicated that the rotor contribution to aircraft stability, $\partial C_M / \partial C_L$ of 0.17, was eliminated by folding the blades resulting in a stable aircraft with a $\partial C_M / \partial C_L$ of -0.29 for both methods of blade folding.

4.5 DYNAMICS

The blades were stable throughout the fold cycle for both flatwise and edgewise folding schemes as determined from visual observation, movies and data from Test Program IV, Reference 1g.

TABLE 4.2 AIRCRAFT WEIGHT SUMMARIES

	BASE-LINE		SCHEME NO.4 FLUSH		SCHEME NO.4 EDGEWISE	
ROTOR GROUP	-		-		-	
WING GROUP	5710		5710		5710	
TAIL GROUP	982		982		982	
BODY GROUP	5980		5980		5980	
BASIC						
SECONDARY						
SECOND.-DOORS, ETC.						
ALIGHTING GEAR	3195		3195		3195	
FLIGHT CONTROLS	3636		3636		3636	
ENGINE SECTION	3061		3061		3141	
PROPULSION GROUP	(16919)		(16801)		(17001)	
ENGINES(S)	2134		2134		2134	
AIR INDUCTION	360		360		360	
EXHAUST SYSTEM						
COOLING SYSTEM	15		15		15	
LUBRICATING SYSTEM	26		26		26	
FUEL SYSTEM	2489		2489		2489	
ENGINE CONTROLS	42		42		42	
STARTING SYSTEM	148		148		148	
PROPELLER INST.	4936		4818		5018	
*DRIVE SYSTEM	4485		4485		4485	
FAN SYSTEM	2284		2284		2284	
AUX. POWER PLANT	182		182		182	
INSTR. AND NAV.	400		400		400	
HYDR. AND PNEU.	292		292		292	
ELECTRICAL GROUP	775		775		775	
ELECTRONICS GROUP	950		950		950	
ARMAMENT GROUP	50		50		50	
FURN. & EQUIP. GROUP	1470		1470		1470	
PERSON. ACCOM.						
MISC. EQUIPMENT						
FURNISHINGS						
EMERG. EQUIPMENT						
AIR COND. & DE-ICING	519		519		519	
PHOTOGRAPHIC						
AUXILIARY GEAR	40		40		40	
MFG. VARIATION	446		446		446	
WEIGHT EMPTY	44607		44489		44769	
FIXED USEFUL LOAD						
CREW (5)	1200					
TRAPPED LIQUIDS	135					
ENGINE OIL						
FUEL	11058					
CARGO	10000					
PASSENGERS/TROOPS						
GROSS WEIGHT	67000					

• INCLUDES —— LH. XMS. OIL

REV.

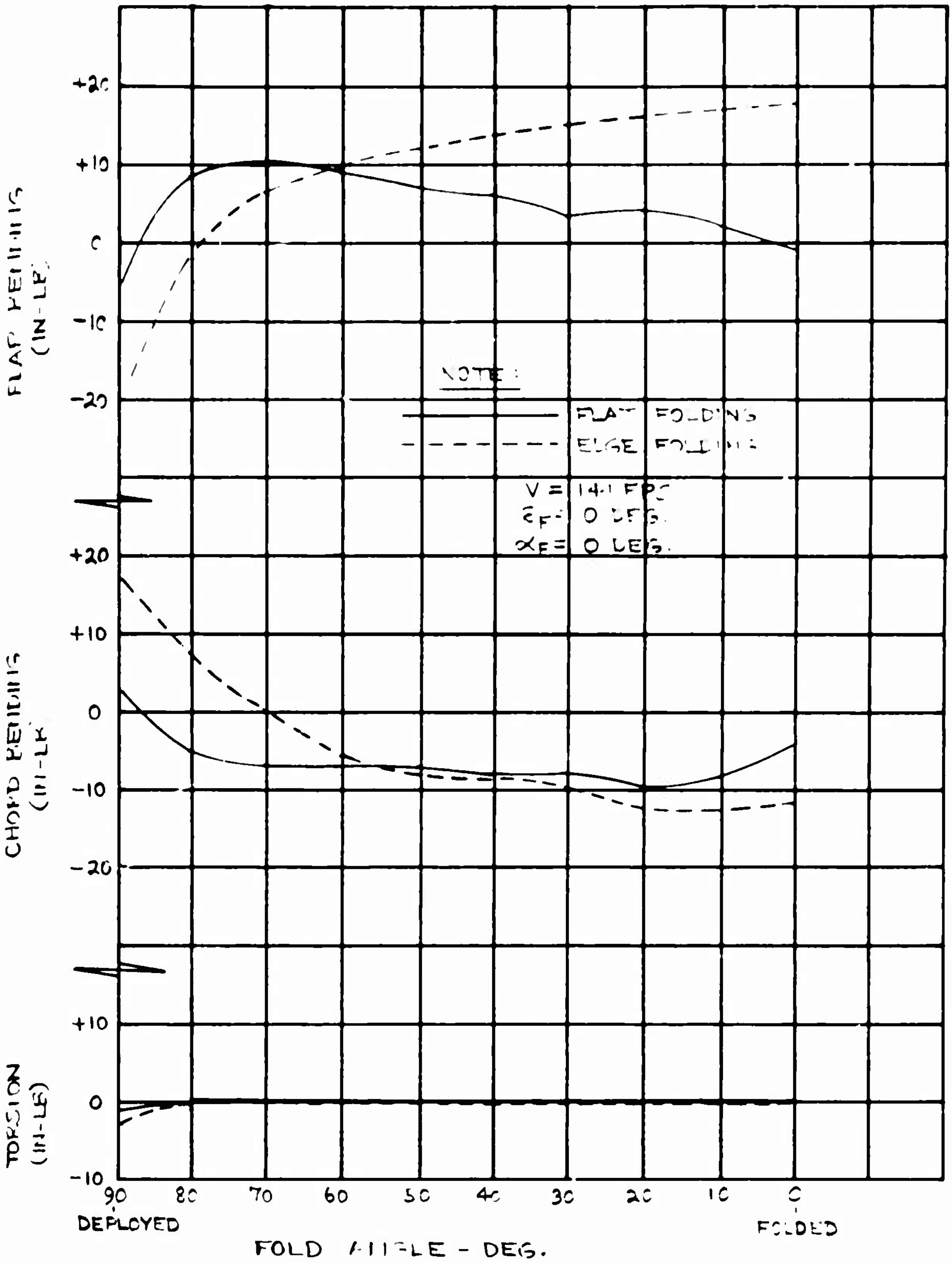


Figure 10. Blade Loads Comparison for Edgewise and Flatwise Fold.

5.0 QUALITY ASSURANCE

In this section the maintainability, reliability and value engineering aspects of the two methods for blade folding, the flat and edgewise, are compared and the four schemes of blade folding, using different concepts are compared.

5.1 MAINTAINABILITY

The assumed mission for the stowed tilt rotor aircraft is to provide tactical air support in forward combat areas. This means that these aircraft will be deployed in small numbers with an absolute minimum of support personnel and equipment. In most cases, several aircraft will be deployed to an unprepared area with only pilots, crew chiefs, and mechanics for operational personnel and only the tools required for daily maintenance and inspections. This element is then expected to function effectively for 2 to 4 weeks before being resupplied with anything more than food and ordinance, during which time there will be no facilities for teardown inspections or repairs to the aircraft, and all maintenance will be performed in the open. In summary, the aircraft along with all of its direct support personnel and equipment, must be self-deployable to meet the USAF tactical aircraft requirements of the 1980's.

In view of the above mission requirements, the following maintainability considerations should be investigated during detailed design. Maintenance manhours cannot be provided at this stage of design until more details are defined.

Maintainability Considerations Common to all Blade Fold Schemes

Lubrication System:

1. Provisions for adequate oil scavenge and filtration system.

2. Method of assuring adequate lubrication of blade retention bearings.

3. Hydraulic leak contamination of lubrication oil.

4. Air-oil mist system precludes access plates in the aerodynamic spinner; complete drainage and removal of spinner is required prior to any inspection or maintenance of rotor stack components.

5. Effects of 90° nacelle rotation.

Hydraulic System:

1. Complex plumbing may not be conducive to connection of diagnostic, prognostic, and functional test equipment.

2. Leakage can contaminate hub and transmission lubricants.

Control Systems:

1. Mechanical flight controls will be highly inaccessible (fly-by-wire could alleviate problem and should be available in the 1980's).

2. Blade folding and unfolding operation will require closed loop sequencing control system common to both nacelles with numerous feedback sensors (and slip rings) on each rotor system.

Blade Tracking:

1. As currently envisioned, this system involves a highly sophisticated and expensive mechanism in the blade retention housing.

2. The tracking adjustment can only be made with the blade folded. Since the blades cannot be folded on the ground, they must be removed and replaced each time a tracking adjustment is made. (It is suggested that adjustable pitch links would solve this problem - if they could be made accessible through the spinner).

Edgewise vs Flat Folding:

1. Edgewise Folding - The edgewise folding only simplifies the rotor kinematics by allowing the pitch change sleeve cam track to be a straight cut rather than a spiral. The load changes may somewhat improve the cam roller follower reliability in the edgewise configuration but the magnitude is not likely to be significant as discussed earlier. The edgewise folding blade wells in the nacelles will require adequate drainage and heating to prevent ice formation and will require pre- post-flight cleaning to prevent accumulation of foreign matter. Any airload distortion of the blade during the final phase of folding could prevent proper alignment of the blade with its well and cause blade/nacelle damage in addition to an aborted fold cycle.

2. Flat Folding - The flat folding scheme requires only the spiral cam track in the pitch change sleeve as a kinematic change to the rotor system. The "scalloped" nacelle shape will be less complex and easier to inspect and repair than the "star" nacelle required for the edgewise folding. Blade alignment with the nacelle during the final phase of folding should be less critical in the flat folding configuration.

Maintainability Considerations of Individual Blade Fold Schemes

Folding Scheme 1

Servicing - No way to identify actuator servicing requirement except by degraded performance. No apparent way to service with fluid. Leakage will contaminate hub lube oil.

Inspection - Visual inspection not possible, functional check not possible on ground, no provisions for test points to allow adequate inspection without physical removal of actuator. This type of inspection is not available to tactical units due to lack of required GSE and skill levels.

Accessibility - Minimum of 30 manhours and intermediate maintenance level GSE/skill levels, are required to remove, inspect, and replace this actuator. "In-the-way" components which must also be removed to gain access are spinner, oil reservoir, rotor blades, cyclic pitch actuators, swashplate, and rotor hub.

Survivability - Inaccessibility will reduce susceptibility to incorrect maintenance (Murphy's Law). Air-oil mist environment will reduce actuator exposure to corrosive agents.

Maintenance Concept - At tactical level, no corrective maintenance actions are feasible. All maintenance, inspections, and repairs would be performed at a higher maintenance level.

Folding Scheme 2

Servicing - None required for sealed electric motor. Trunnion mounted ball nut must have provisions for integral wiping and lubrication of jackscrew portion of actuator. Periodic filling of trunnion mounted ball nut with suitable lubricant will be required.

Inspection - Pre and post-flight inspection of actuator for security of attaching hardware and electrical connections. (Motor is hermetically sealed and not conducive to internal inspection). Functional checks are possible for troubleshooting.

Accessibility - Completely accessible with no in-the-way components and a remove and replace task time of 0.25 manhours. However, slip ring requirements may complicate this design.

Survivability - To minimize exposure of jackscrew to the environment, an elastomeric dust cover should be provided between the trunnion mounted ball nut and the outboard end of the jackscrew. This will restrict jackscrew exposure to the environment to those periods when the aircraft is in forward flight with the rotors stowed in the nacelles. Hermetically sealed motor is not exposed to the environment. Since the actuator is not an in-the-way component during inspection, and requires no mechanical adjustments after initial installation, it has a low exposure to Murphy's Law.

Maintenance Concept - Purely remove and replace at tactical level with repair actions only at depot level.

Folding Scheme 3

Servicing - Hydraulic actuators do not require servicing but the actuator ring and slider face must be cleaned prior to each flight.

Inspection - Inspect actuators for evidence of leakage, actuator ring and slider face for cleanliness and wear, hardware for cracks and security of attachment.

Accessibility - All blade fold components are very accessible but the four actuators, eight fold links, actuator ring, slider face and "oil can" are all "in-the-way" items for any maintenance actions on the cyclic pitch actuators, swashplate, pitch links and internal hub components. The "oil can" structure must be relatively heavy to handle the fold link loads and prevent the actuator ring from "cocking" on the slider face in the event of single actuator failure. Because of this it is unlikely that access plates can be provided in this section of the spinner.

Survivability - Design is "Murphy Proof" from a maintenance point of view but exposed actuator ring and slider face will be susceptible to abrasion and corrosion.

Maintenance Concept - At the tactical level, maintenance will be limited to remove and replace actions with repairs and overhauls being performed at the Intermediate Maintenance level.

Folding Scheme 4

Scheme IV proposes the use of a fail operational hydraulic jackscrew actuator in place of the actuators proposed in Method 2. The five discussed areas of maintainability are not significantly impacted by this change.

5.2 RELIABILITY

The Reliability analysis of the four rotor fold systems under consideration was performed using the following assumptions.

1. Only Flight Safety malfunctions were considered. (Flight Safety malfunctions in this instance are defined as complete loss of function of any component within the system).

2. By dictum, the rotary wing mode of operation comprises 20% of total aircraft flight hours. The entire 20% rotary wing exposure time was applied against the in-flight blade folding function.

3. The rates presented here have been adjusted to reflect total aircraft flight hours.

4. The rates predicted herein assume that; (a) a normal aircraft type inspection will be performed, or (b) condition monitoring aids will be incorporated, or (c) low TBO removal times will be in effect.

CH-46/CH-47 major accident rates were used (with adjustments mentioned above) where similarity to component structure, environment, and function were apparent. In addition, failure rate data (FARADA) handbooks were used to assist in making reasonable failure predictions.

A comparison of the four systems shows that the main difference is confined to the blade fold force producing mechanisms.

Scheme 1 uses a rotary hydraulic actuator and drive plate, an inner fold link (which is comparable to a pitch change link in function) and for each blade a cam track, follower, piston and cylinder. The cam track changes from straight line to helical mode near the end of its travel to rotate the blade for flat folding.

Scheme 2 uses four electro mechanical jackscrew actuators to provide the motivation required to fold the four blades.

Scheme 3 uses individual hydraulic actuators, and links for each blade driven through a common slider assembly to accomplish the blade folding.

Scheme 4 is the same as 2 but uses hydraulic jackscrews to provide motive force.

Schemes 1 and 4 appear to be the most reliable, and of these Scheme 4 is better since it uses a fail-operational actuator with fully duplicated functions.

Scheme 3 has the most operating components, thus a higher failure potential. Its components, like those of 2 and 4 are exposed to the elements, an advantage for inspections but a liability from a reliability view. Also, unsymmetrical folding line and/or actuator loads make the slider ring highly susceptible to "cocking" which would jam the system.

Although it is understood that these are preliminary numbers, based on limited design visibility, and are not absolute values, they are representative of the <u>relative</u> merit of the systems considered.

It is apparent, however, that advanced state-of-the-art techniques must be employed to the maximum degree in any design of this critical nature to provide acceptable flight safety performance. The flight safety (major accident) rate for the entire CH-47C aircraft (total <u>all</u> systems) caused by material failures is 43 per million flight hours. The predicted number for the 347 model 106 is 25 per million, of which the autophase system was allowed one per million.

TABLE 5.1 RELATIVE RELIABILITY SUMMARY

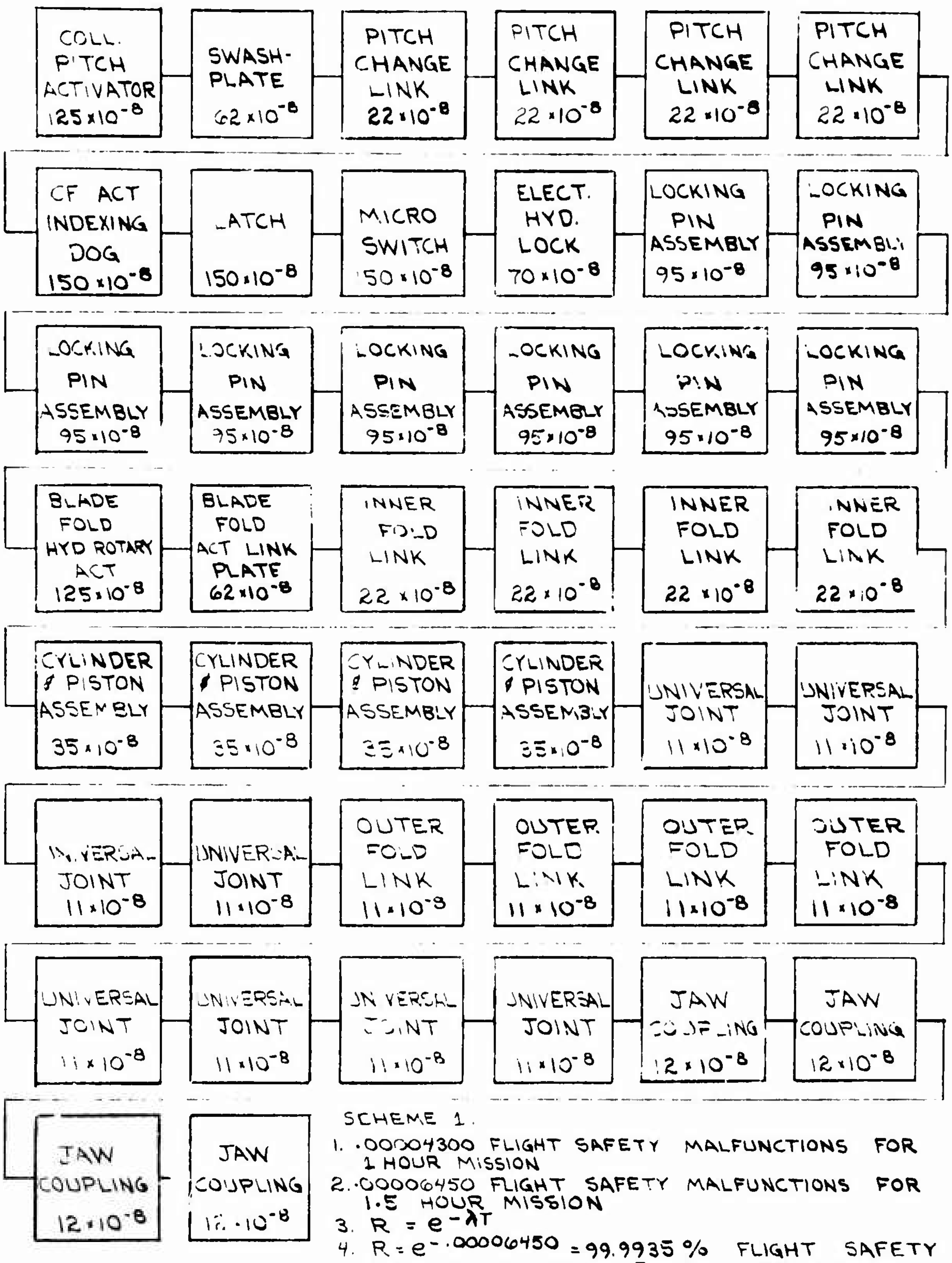
SCHEME	SAFETY RELIABILITY	CATASTROPHIC FAILURES* PER MILLION FLIGHT HOURS
1	99.9957	43.00
2	99.9948	50.78
3	99.9948	51.70
4	99.9965	35.18
CH-47C (Total A/C)	99.9957	43.00
347-106 (Total A/C)	99.9975	25.00

*Catastrophic failure means that there is a complete stoppage of the folding system. Since the stowed tilt rotor aircraft has wings and a fan propulsion system and would be flying on these during folding/unfolding, a catastrophic failure may not result in the loss of the aircraft.

TABLE 5.2 SCHEME 1 RELIABILITY SUMMARY

COMPLETE LOSS OF FUNCTION IN-FLIGHT BLADE FOLD SYSTEM

SEQ.	DESCRIPTION OF COMPONENT	QPA	R COMPONENT	R SYSTEM
1	Collective Pitch Actuator	2	.00000125	.00000250
2	Swashplate	2	.00000062	.00000124
3	Pitch Change Links	8	.00000022	.00000176
4	C.F. Act. Indexing Dog.	2	.00000150	.00000300
5	Latch	2	.00000150	.00000300
6	Micro Switch	2	.00000150	.00000300
7	Electrical Hyd. Lock	2	.00000070	.00000140
8	Locking Pin Assy	16	.00000095	.00001520
9	Blade Fold Hyd. Rotary Act.	2	.00000125	.00000250
10	Blade Fold Act. Link Plate	2	.00000062	.00000124
11	Inner Fold Link	8	.00000022	.00000176
12	Piston Assembly & Cylinder	8	.00000035	.00000280
13	Universal Joint	16	.00000011	.00000176
14	Outer Fold Link	8	.00000011	.00000088
15	Jaw Coupling	8	.00000012	.00000096
		88		.00004300



SCHEME 1.

1. .00004300 FLIGHT SAFETY MALFUNCTIONS FOR 1 HOUR MISSION
2. .00006450 FLIGHT SAFETY MALFUNCTIONS FOR 1.5 HOUR MISSION
3. $R = e^{-\lambda T}$
4. $R = e^{-.00006450} = 99.9935\%$ FLIGHT SAFETY RELIABILITY FOR 1.5 HOUR MISSION.

Figure 11. Reliability Functional Block Diagram for Scheme 1

TABLE 5.3 SCHEME 2 RELIABILITY

COMPLETE LOSS OF FUNCTION IN-FLIGHT BLADE FOLD SYSTEM

SEQ.	DESCRIPTION OF COMPONENT	QPA	R COMPONENT	R SYSTEM
1	Collective Pitch Actuator	2	.00000125	.00000250
2	Swashplate	2	.00000062	.00000124
3	Pitch Change Link	8	.00000022	.00000176
4	C.F. Act. Indexing Dog.	2	.00000150	.00000300
5	Latch	2	.00000150	.00000300
6	Micro Switch	2	.00000150	.00000300
7	Electrical Hydraulic Lock	2	.00000070	.00000140
8	Locking Pin Assembly	16	.00000095	.00001520
9	Electro-Mech. Jackscrew Act.	8	.00000195	.00001560
[illegible]	Piston Assy. & Cylinder	8	.00000028	.00000224
11	Universal Joint	16	.00000004	.00000064
12	Fold Link	8	.00000003	.00000024
13	Jaw Coupling	8	.00000012	.00000096
		84		.00005078

SCHEME 2

1. .00005078 FLIGHT SAFETY MALFUNCTIONS FOR 1 HOUR MISSION
2. .00007617 FLIGHT SAFETY MALFUNCTIONS FOR 1.5 HOUR MISSION
3. $\underline{R} = e^{-\lambda t}$
4. $R = e^{-0.00007617} = \underline{R} = 99.9924\ \%$

Figure 12. Reliability Functional Block Diagram for Scheme 2.

TABLE 5.4 SCHEME 3 RELIABILITY

COMPLETE LOSS OF FUNCTION - IN-FLIGHT BLADE FOLD SYSTEM

SEQ.	DESCRIPTION OF COMPONENT	QPA	R COMPONENT	R SYSTEM
1	Collective Pitch Actuator	2	.00000125	.00000250
2	Swashplate	2	.00000062	.00000124
3	Pitch Change Link	8	.00000022	.00000176
4	C.F. Act. Indexing Dog.	2	.00000150	.00000300
5	Latch	2	.00000150	.00000300
6	Micro Switch	2	.00000150	.00000300
7	Electrical Hyd. Lock	2	.00000070	.00000140
8	Lock Pin Assy	16	.00000095	.00001520
9	Blade Fold Hy. Actuator	8	.00000125	.00001000
10	Slider	2	.00000062	.00000124
11	Blade Fold Fixed Link	16	.00000033	.00000528
12	Cylinder & Piston Assy	8	.00000028	.00000224
13	Universal Joint	16	.00000004	.00000064
14	Fold Link	8	.00000003	.00000024
15	Jaw Coupling	8	.00000012	.00000096
		102		.00005170

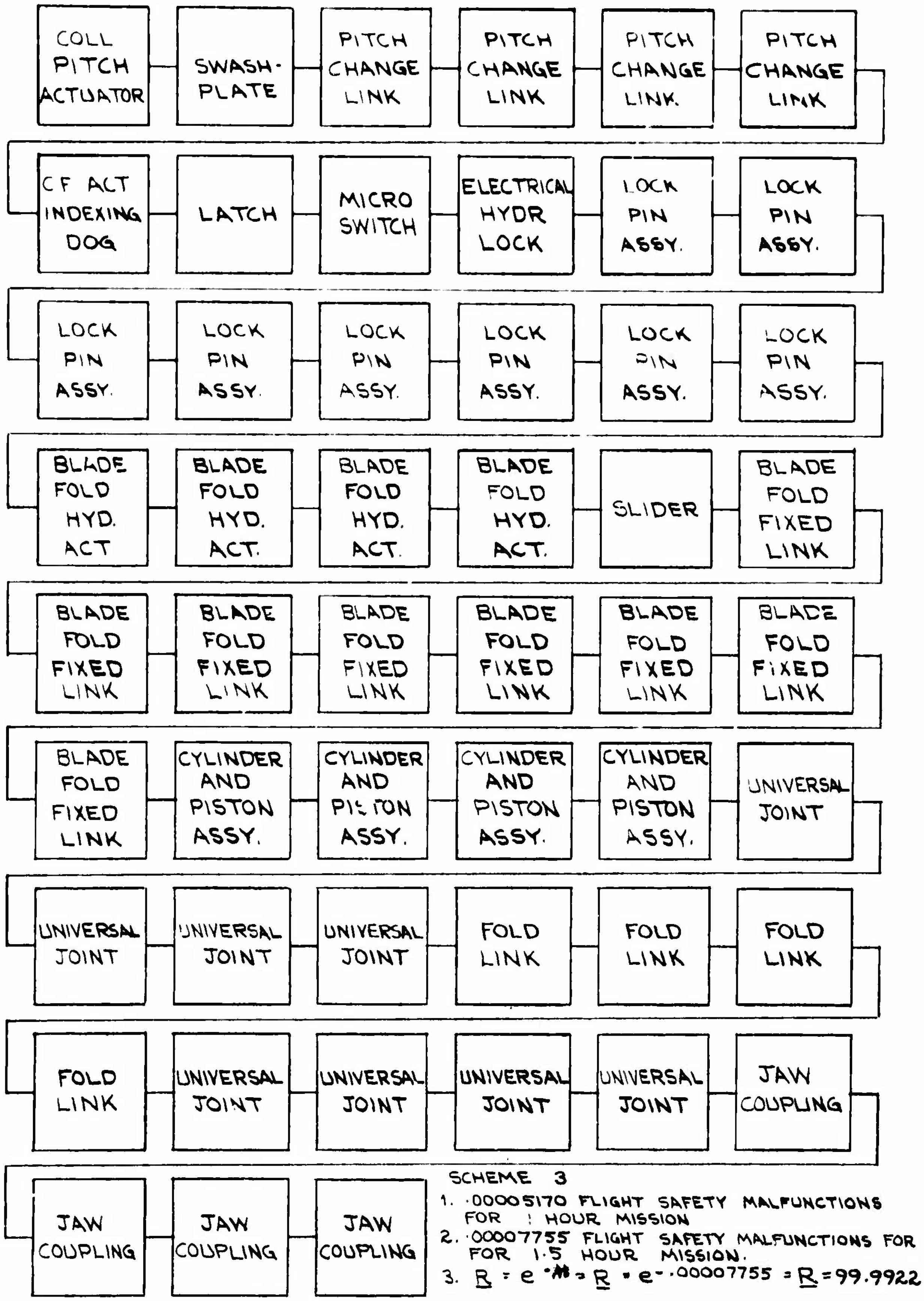
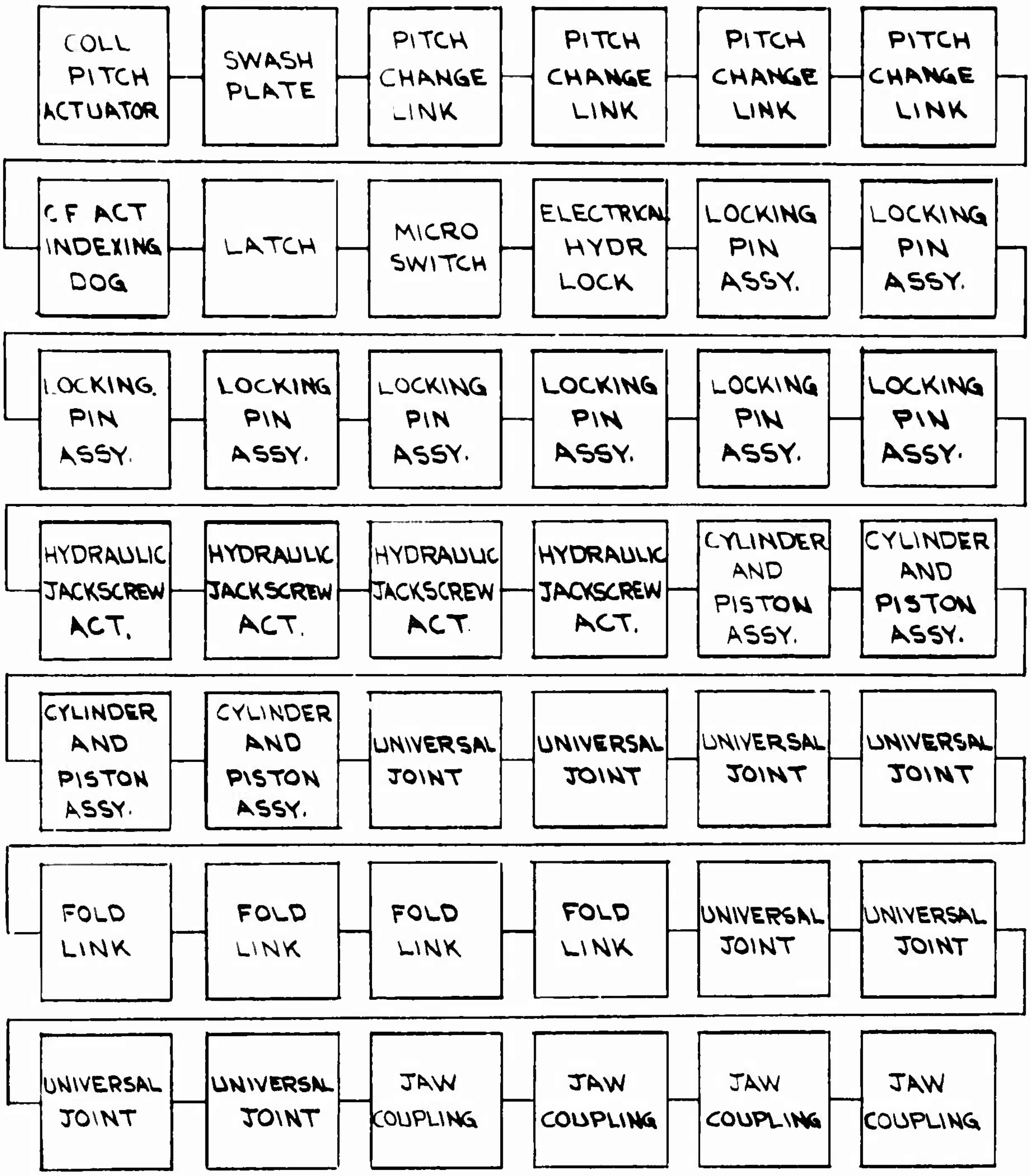


Figure 13. Reliability Functional Block Diagram for Scheme 3

TABLE 5.5 SCHEME 4 RELIABILITY

COMPLETE LOSS OF FUNCTION - IN-FLIGHT BLADE FOLD SYSTEM

SEQ.	DESCRIPTION OF COMPONENT	QPA	R COMPONENT	R SYSTEM
1	Collective Pitch Actuator	2	.00000125	.00000250
2	Swashplate	2	.00000002	.00000124
3	Pitch Change Link	8	.00000022	.00000176
4	C.F. Act. Indexing Dog.	2	.00000150	.00000300
5	Latch	2	.00000150	.00000300
6	Micro Switch	2	.00000150	.00000300
7	Electrical Hydraulic Lock	2	.00000070	.00000140
8	Locking Pin Assembly	16	.00000095	.00001520
9	Hyd-Mech. Jackscrew Act.	8	$3x10^{-13}$	$3x10^{-13}$
10	Piston Assembly & Cylinder	8	.00000028	.00000224
11	Universal Joint	16	.00000004	.00000064
12	Fold Link	8	.00000003	.00000024
13	Jaw Coupling	8	.00000012	.00000096
		84		.00003518



SCHEME 4

1. .00004878 FLIGHT SAFETY MALFUNCTIONS FOR 1 HOUR MISSION
2. .00007317 FLIGHT SAFETY MALFUNCTIONS FOR 1.5 HOUR MISSION
3. $\underline{R} = e^{-\lambda t} = \underline{R} = e^{-.00007317} \cdot \underline{R} = 99.9927$

Figure 14. Reliability Functional Block Diagram for Scheme 4

5.3 VALUE ENGINEERING

Value Engineering provided the support during various periods of design for the stowed tilt rotor systems. The object of the value studies was to analyze the functional intent of alternate design concepts with respect to the total requirement and to indicate cost excesses existent in each alternative approach prior to concept selection. The essential elements of MIL-V-38352 were used as the method of operation.

Two different studies were performed. The first was a comparison between flatwise and edgewise folding of the rotor blades. Four different methods of actuation were compared. The second study was aimed at reducing the cost of the hub structure.

In order to arrive at the relative value of each alternate, the following steps were followed in the studies:

1. Functional analysis

2. Development of alternatives

   An example of this is shown for the basic vs the clamshell hub concept

3. Cost analysis of alternates by:

   (a) Procuring vendor forging costs both recurring and non-recurring.

   (b) Determining manufacturing in-house fabrication manhours with the use of standard shop industrial engineering data, factory efficiency factors, cosmetic factors, etc., for unit value at 100 units.

   (c) Applying the improvement values for 00 units/250 aircraft with Boeing-Vertol methodology for cumulative values for 500 units.

   (d) Applying the 1971 Boeing-Vertol dollar rates which are comparable to the industry average dollar rates.

   (e) Determining the rate tooling costs from in-house estimates.

   (f) Completing detail value engineering detail cost study sheets to support the value engineering final cost analysis charts.

Costing System and Ground Rules

A combination of detailed standard data, historical costing data and Boeing-Vertol pricing structure were applied to the design concepts. Costs are based on production quantity of 250 aircraft manufactured for 1971 dollar rates. Adjustment for the escalation of dollars over the next decade has not been included.

1. Costs include direct, burden and G & A. Profit has not been included.

2. Costs for common items to all four schemes have been excluded from the system configuration tradeoff study.

3. Estimates are preliminary and are valid for comparison purposes only and are not related to selling price.

Folding Scheme and Actuator Tradeoff

Four alternate schemes were evaluated not only for subsystem interfaces that are high in costs or degree of complexity but also to determine production feasibility and delta costs for each alternate scheme. Based on the degree of information, illustrated on preliminary layouts for Schemes 2, 3 and 4, the approach to obtain the delta costs was to eliminate all items that are common to the four schemes. The common items were selected from Figure 3 which shows the baseline scheme with rotary hydraulic actuator.

Table 5.6 shows a summary of the results and indicates that the flat fold scheme with actuation by electric jackscrews (folding method number 2) is the most economical system from a cost point of view; however, Scheme 4 can be designed using one failsafe actuator with a linkage to move all blades simultaneously and this can reduce the cost of Scheme 4 by approximately $7000 per aircraft which will make Scheme 4 comparable to Scheme 2 in cost.

Two sets of recurring cost numbers are shown in Table 5.6, the cost as estimated from the preliminary drawings and the anticipated production cost, based on a value judgment of further optimization of the design. The cost numbers in Table 5.6 also reflect the following risk and high cost areas:

1. All Folding Methods

   (a) Locking mechanism for locking rotor blade in operation.

   (b) Cam for flat fold blades

TABLE 5.6 STOWED TILT ROTOR ALTE

THE COSTS AS SHOWN DEPICT DELTA DO

CONCEPT	RECURRING COSTS PER AIRCRAFT (PRODU					
	ROTARY ACTUATOR	PISTON	INNER LINK / STRUT	ELECTRIC ACTUATOR	LUGS HUB & ROOT END	HYDR. ACTU
SCHEME No. 1 (BASELINE)	$20,000	$1,584	$960	—	—	—
SCHEME No. 2	—	$720	—	$6,592	$140	—
SCHEME No. 3	—	$720	$1,440	—	$50	$6,4
SCHEME No. 4 (SAME AS No. 2 EXCEPT ACTUATOR)	—	$720	—	—	$140	$12,(

	RECURRING COST PER A/C		
	NACELLE STRUCT.	PISTON	
BLADE FLAT - FOLD		$38	
BLADE EDGEWISE FOLD	$19,320		

B

TERNATE DESIGN CONCEPTS SUMMARY

DOLLARS - COSTS OF COMMON ITEMS TO ALL CONCEPTS ARE EXCLUDED.

DUCTION QUANTITY 250 A/C)				RECURRING COSTS			
				PER PRELIMINARY DWG'S		ANTICIPATED PROD. COST.	
YDRAULIC CTUATOR	MOUNTING & ACTUATOR RING ASSY.	SLIDE PLATE & BEEF-UP OIL CAN	INSTALLATION TO ASS'Y.	PER AIRCRAFT	PER 250 A/C CONTRACT	PER AIRCRAFT	PER 250 A/C CONTRACT
—	—	—	$8,726	$31,264	$7,816,000	—	—
—	—	—	$4,316	$11,768	$2,942,000	$14,168	$3,542,000
6,400	$900	$1,944	$5,800	$17,254	$4,313,500	$18,854	$4,713,500
12,800	—	—	$5,580	$19,240	$4,810,000	$20,840	5,210,000
				$38	$9,500		
				$19,320	$4,830,000		

2. Folding Method #1

   (a) High cost of development of the hydraulic actuator.

3. Folding Method #3

   (a) Synchronization of the hydraulic actuators for the sliding ring.

   (b) Binding of the swashplate in the track due to loading.

The above items are isolated as probable technical risk areas and there is no reliable means to determine the degree of production cost at this date. However, the anticipated production costs shown in Table 5.6 indicates a presumed estimate.

Value Engineering Analysis of the Hub Structure

The rotor hub design concept illustrated in Figure 3 was selected for a detail cost selection study because of the high cost for machining and material scrappage during fabrication of the integral one piece unit. An alternate clamshell concept consisting of two halves bolted together was considered as a substitute. Detail layouts (Figure 15) were completed to prove clamshell feasibility and to provide cost evaluation. Two materials 6AL-4V titanium and 4340 steel were analyzed. Sealing for the clamshell concept will be provided by "O" ring seal in a groove at the mating surfaces.

Tables 5.7 and 5.8 show the clamshell hub concept is 24% cheaper for a steel hub and 23% cheaper for a titanium hub. The cost of hubs for 250 aircraft is shown in Figures 16 and 17. Figures 18 and 19 show the improvement in manufacturing hours per hub with number of hubs.

VALUE ENGINEERING
COST STUDY SHEET

DATE: 6-23-71
V.E. NO.: 101P

TABLE 5.7 STEEL HUB PRODUCTION COST PER AIRCRAFT

TITLE: HUB - STOWED TILT ROTOR

DRAWING: 213-10400 MATL. 4340 STEEL

DESCRIPTION: THIS SHEET SHOWS PRELIMINARY PRODUCTION COSTS PER A/C, BASED ON 250 A/C PRODUCTION

COSTS & SAVINGS TO IMPLEMENT THIS CHANGE IS AS FOLLOWS:

ITEM	NON-RECURRING		RECURRING PER A/C	
	INTEGRAL	CLAMSHELL	INTEGRAL	CLAMSHELL
ENGINEERING	--	--	--	--
TOOLING(PRODUCTION)	$ 75,000	$100,000	--	--
MANUFACTURING	--	--	$10,856	$ 7,300
MATERIAL	--	--	22,584	17,630
SERVICE ENGRG.	--	--	--	--
MFG. PECULIAR TO CLAMSHELL	--	--	--	548
VENDOR TOOLING	55,500	135,700	--	--
TOTAL	$130,500	$235,700	$33,400	$25,478

IMPLEMENTATION COST -

SAVINGS/COST PER A/C =

BREAK EVEN POINT =

VALUE ENGINEER

VALUE ENGINEERING
COST STUDY SHEET

DATE: 6-10-71
V.E. NO.:101P

TABLE 5.8 TITANIUM HUB PRODUCTION COST PER AIRCRAFT

TITLE: HUB-STOWED TILT ROTOR

DRAWING: 213-10400 MATL. TITANIUM 6AL-4V

DESCRIPTION: THIS SHEET ILLUSTRATES PRELIMINARY PRODUCTION COSTS PER A/C, BASED ON 250 A/C PRODUCTION

COSTS & SAVINGS TO IMPLEMENT THIS CHANGE IS AS FOLLOWS:

ITEM	NON-RECURRING		RECURRING PER A/C	
	INTEGRAL	CLAMSHELL	INTEGRAL	CLAMSHELL
ENGINEERING				
TOOLING(PRODUCTION)	$ 75,000	$100,000		
MANUFACTURING			$16,908	$10,030
MATERIAL			61,356	49,440
SERVICE ENGRG.				
MFG. PECULIAR TO CLAMSHELL				764
VENDOR TOOLING	59,000	161,000		
TOTAL	$134,000	$261,000	$78,264	$60,234

IMPLEMENTATION COST -

SAVINGS/COST PER A/C =

BREAK EVEN POINT =

VALUE ENGINEER

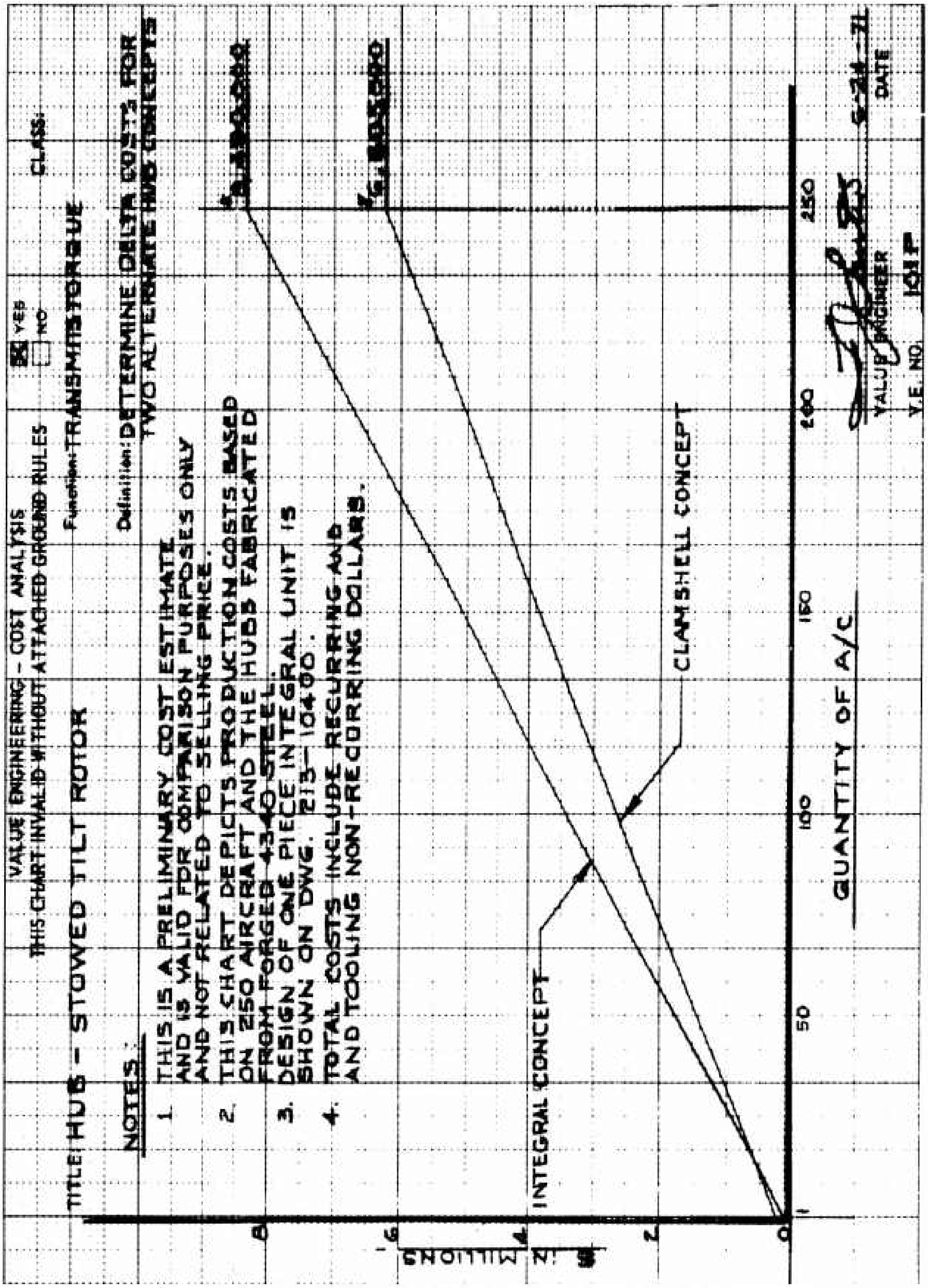


Figure 16. Cost of Steel Hubs for 250 Aircraft

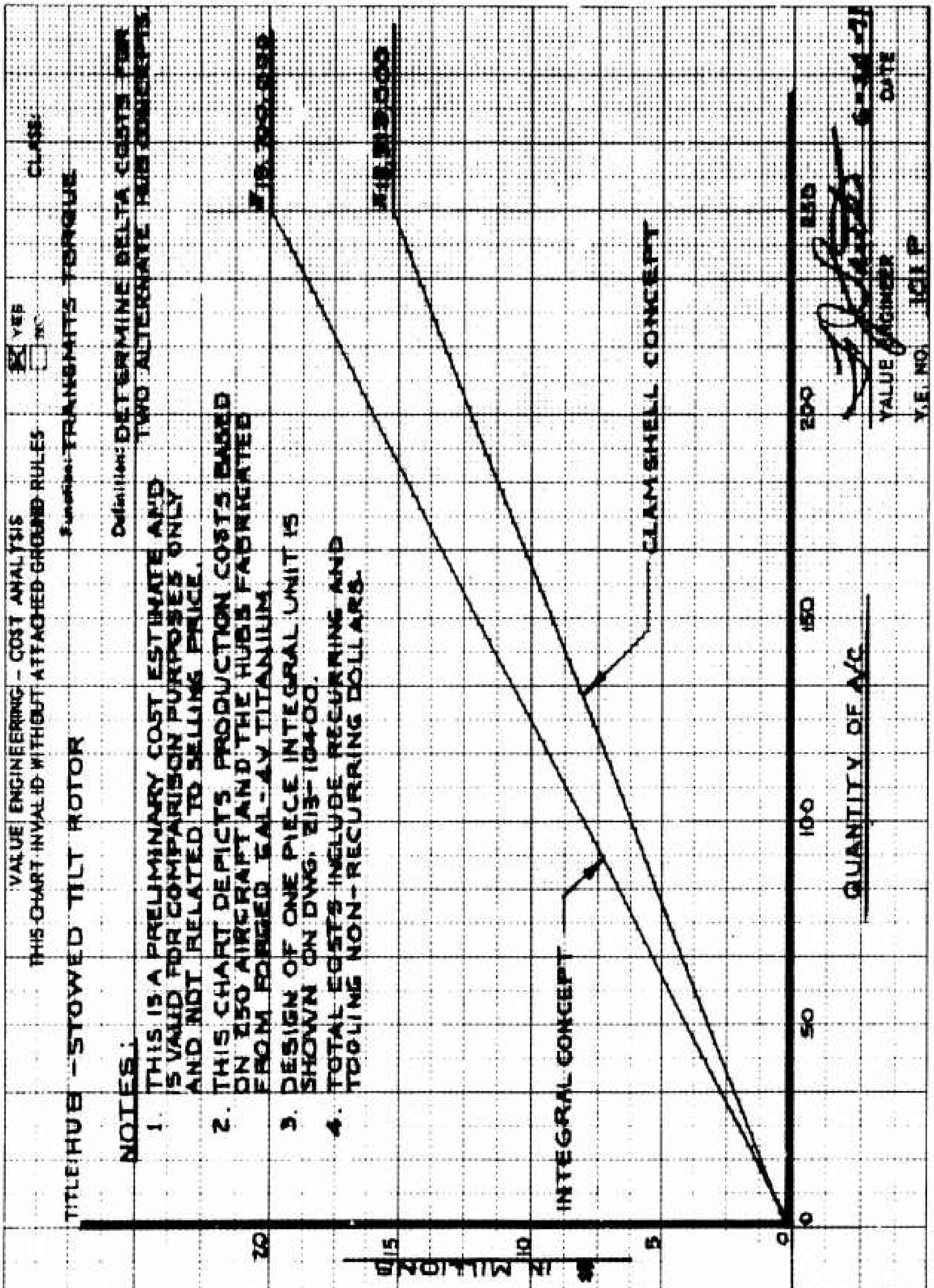


Figure 17. Cost of Titanium Hubs for 250 Aircraft

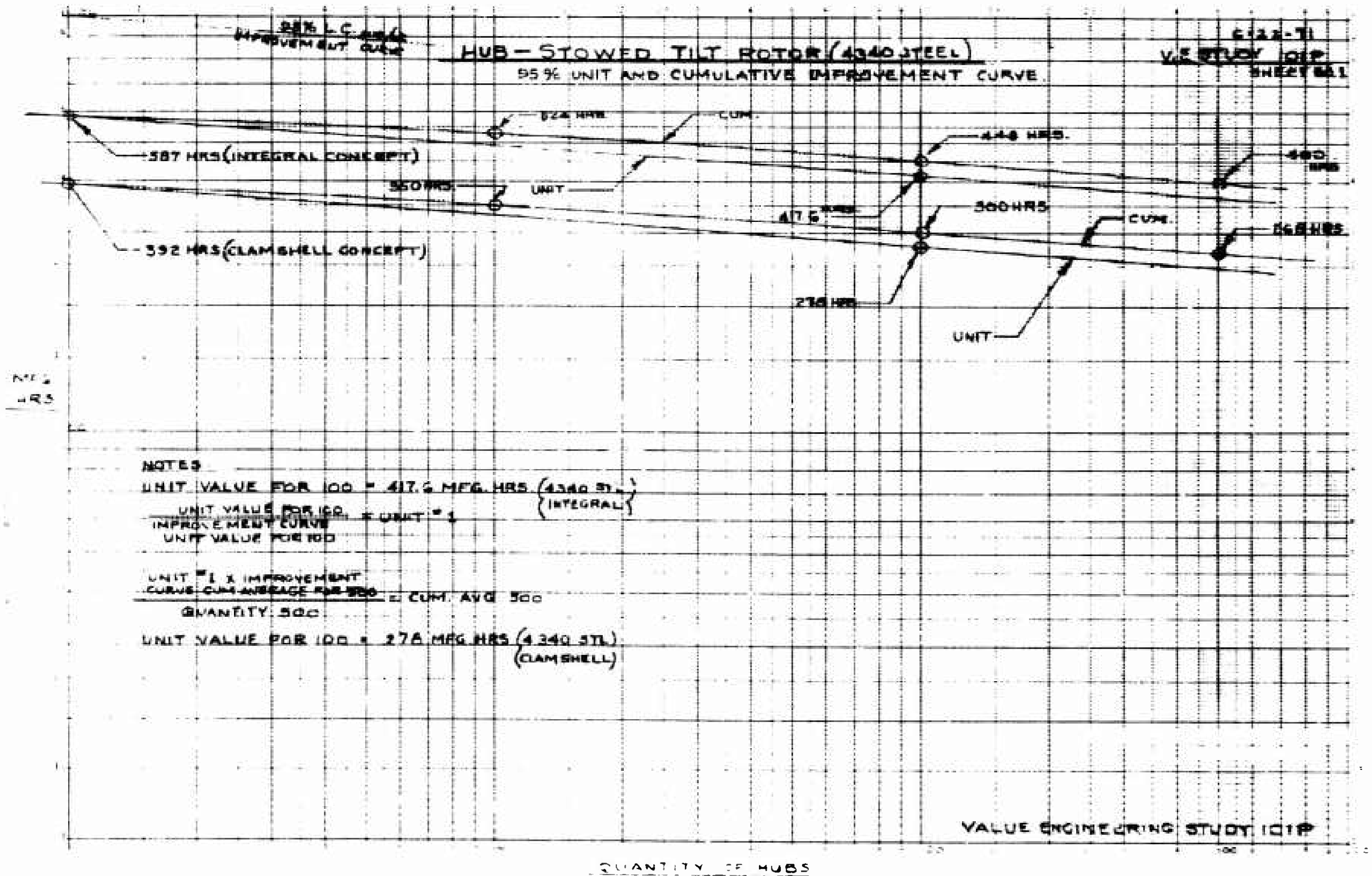


Figure 18. Manufacturing Hours Per Steel Hub

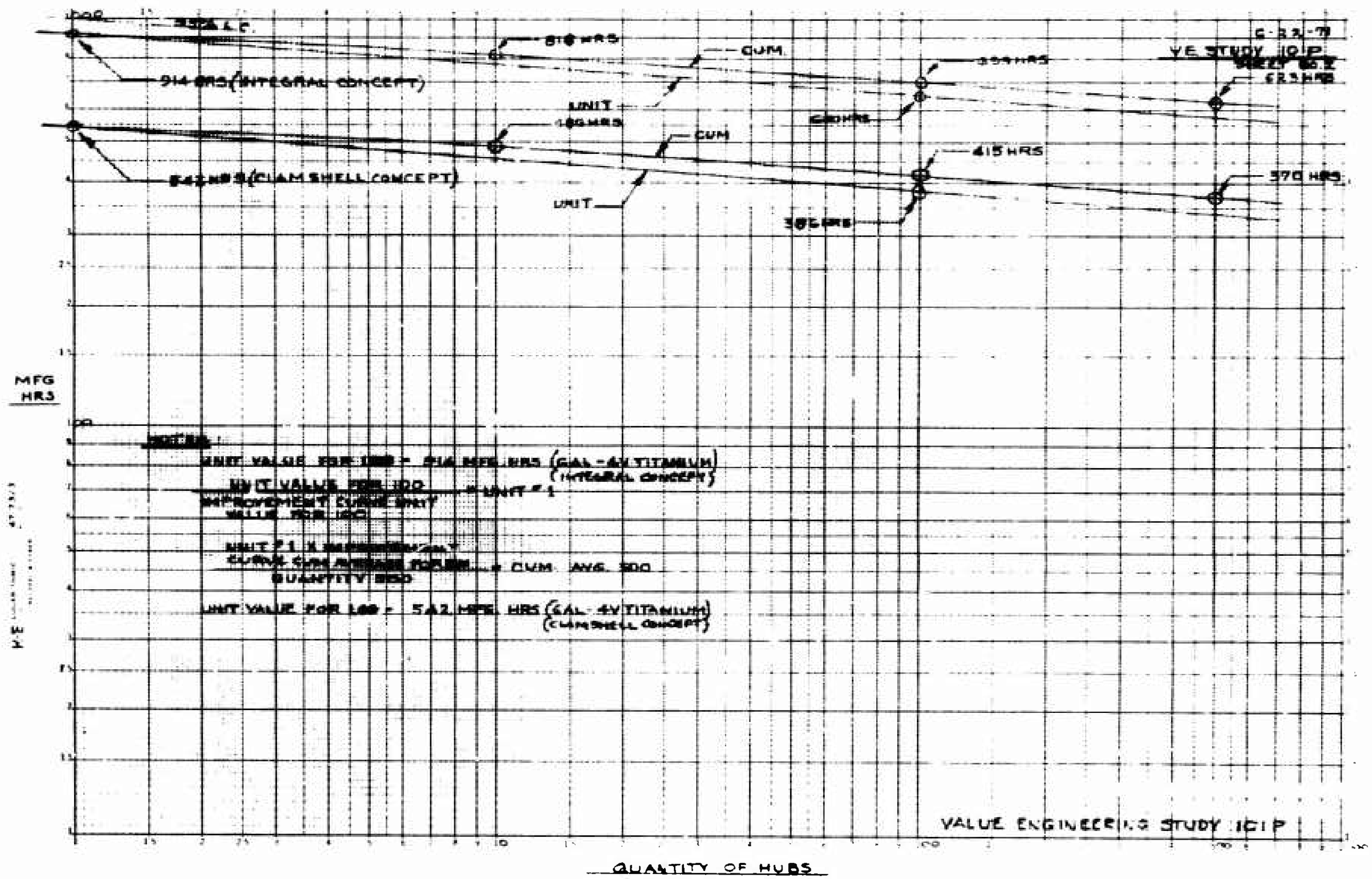


Figure 19. Manufacturing Hours Per Titanium Hub

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(e)	Volume V	Wind Tunnel Test of a Powered Tilt Rotor Performance Model
(f)	Volume VI	Wind Tunnel Test of a Powered Tilt Rotor Dynamic Model on a Simulated Free Flight Suspension System
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